DESIGN AND CONSTRUCTION OF A MODEL ELECTROMAGNETIC SUBMARINE

by

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ABSTRACT

This study recounts the approach taken and the problems which arose in the design, construction, and test of a 900 pound displacement submarine propelled by Lorentz electromagnetic forces in the surrounding sea. This project was carried out by a group of eight senior mechanical engineering students under the direction of the writer at the University of California at Santa Barbara in 1966.

The model carried its own energy source (storage batteries). It had built-in depth regulation and required no umbilical connections, either for power or control purposes. It achieved a cruising speed in excess of 0.40 meters/second.

The case study presents the design objectives, and the design alternatives, and discusses internal duct propulsion, the two-pole external field system, the optimum electromagnets, a comparison of internal and external duct flow systems, the propulsion calculations at design conditions, the electrical system design, the structural design problems, the assembly problems, the preparation for test, the test experience, and a summary of the unanticipated problems.

Prepared with the support of the National Science Foundation. NOTE: The submarine model is presently owned by and located at the Department of Mechanical Engineering, University of California, Santa Barbara, and may be inspected there. Any inquiries regarding this case study or questions relating to the design should be addressed to: Dr. Stewart Way, Consultant, Westinghouse Research and Development Center, Pittsburgh, Pa. 15255.

1. THE PROBLEM PRESENTED

It has been known for a number of years that a ship or submarine could be propelled by means of electromagnetic forces. The method involves the establishment of a magnetic field in a region of the sea water, and the sending of an electric current through this region in a direction generally normal to the magnetic field. In this way a Lorentz body force is produced. The sea water may be driven in a rearward direction and a reaction force acts on the magnet, propelling the boat forward.

Several papers have been published discussing this propulsion system (Refs. 1----6).

It appeared that it would be a worthwhile project, both from the standpoint of furthering engineer technology, and from the standpoint of educational interest, to construct a working model of an electromagnetically propelled submarine.

The problem presented was, then, to design, and ultimately to construct, a submarine model using Lorentz forces for propulsion. The model would of necessity have to be of a size and degree of simplicity matching the local fabrication facilities of the University and surrounding community, and the time available for its completion, which was about five months. Technically, the foremost problem was to insure that the total weight of the structure, energy source and propulsion system was less than or equal to the weight of the displaced water, while realizing a running speed in the model sufficiently high to be of interest. It was felt that this cruising speed should be at least 0.30 meters per second; actually, a higher design speed was realized.

Another ground rule that was adopted was that the model would have to carry its own energy source, rather than being supplied with power by electric cable. No umbilical connections were to be used, either for power or control purposes.

The submarine would have to have built-in means of depth regulation.

The cruising time would have to be sufficiently long to be of interest. A time of 20 minutes was set as a design goal.

2. DESIGN ALTERNATIVES

Before beginning even a preliminary design it was necessary to review certain design alternatives. This called for giving some thought to various ways of moving sea water through or around the hull of a submarine, by electromagnetic means.

The design group was asked to give some thought to the various possibilities, calling on whatever general knowledge they might have of d.c. motors, induction motors or electromagnetic pumps. After some reflection on these matters, the group examined and discussed the various possibilities. Some of these are represented in Figs. 1a,b,c,d.

It is seen that one might use either a duct flow system or an external field system. Also, a choice may be made between a d.c. arrangement and a travelling wave arrangement. The latter resembles a linear induction motor. A permanent magnet or an electromagnet could be used. (Though a superconducting magnet would be appropriate in a large submarine, it would be economically unfeasible for this project.)

It appeared that from the standpoints of simplicity of construction of the model, as well as higher ultimate potential interest (varying magnetic fields difficult with superconducting magnets), a d.c. system should be used. To avoid the procurement problems of a large permanent magnet, that type of magnet was also eliminated at an early stage. Though detailed calculations were not made, there was an intuitive feeling, also, that it might be difficult to meet the buoyancy requirements were a permanent magnet to be used. The choice thus narrowed down to use of either the internal duct or external field configuration, arranged for crossed-field d.c. operation, and embodying an electromagnet.

Another set of design alternatives pertained to the source of electrical power. Exotic converters such as thermoelectric or thermionic systems were ruled out as being not necessary for the present model, and overly expensive, and too demanding of the time available. (Design and construction of an exotic type converter of several k.w. rating is a long term expensive project.) The logical choice appeared to narrow down to use of storage batteries, or a generator driven by an internal combustion engine. Here, again, considerations of simplicity and available time led to the choice of storage batteries, but only after the group had satisfied itself that the buoyancy and performance requirements could be met by batteries. If that had not been possible, we would have gone to the engine driven generator. One need only note that a pound of gasoline contains over 5000 watt hours of chemical energy, and even if this is used at only 20 percent efficiency the resulting 1000 watt hours per pound is far greater than the 10-15 watt hours per pound one gets from conventional batteries. The engine-generator 3-5 kw is also a light-weight device that could easily be carried by the model, so a real power and cruising time advantage would have resulted by use of the engine-generator. Other groups may wish to pursue this line. A snorkel arrangement would need to be provided.

Finally, there was the necessity of deciding on the approximate size for the model. Elementary considerations indicate that to obtain best performance, as large a size as possible should be used. Thus, doubling of hull dimensions increases displacement by a factor of 8 while increasing drag and thrust power requirements only by a factor of 4. Even if we

assumed no improvement in propulsive efficiency by going to larger size, it is evident that a longer cruising time could be realized by using a larger scale. A trade-off can also be made to obtain higher cruising speed, while limiting the duration of running to the same time as for the smaller model.

From these simple considerations it was decided that the model should be as large as possible, in the light of material costs, machine shop capabilities, time for construction and handling problems. The local lathes could handle parts of about 20" diameter with internal chucking. It was estimated that an 18" diameter model would displace 800 to 900 lbs, which, though large, could still be handled, pushed through doorways on dollies, etc.

The approximate dimensions initially decided upon were, therefore, a length of 10 feet, a diameter of about 18" and a displacement of about 900 lbs. The choice of L/d ratio was, in the course of the design, considered in more detail; it has a bearing on minimum drag. In the initial stages, dimensions closer to $L = 2.5$ meters and $d = 0.5$ meters were considered.

The next two sections of this study will take up technical discussions of the internal duct system and the external flow system. In the Santa Barbara project, one part of the design team reviewed the pros and cons of these two systems. Particular attention was given to the total weight of the propulsion components.

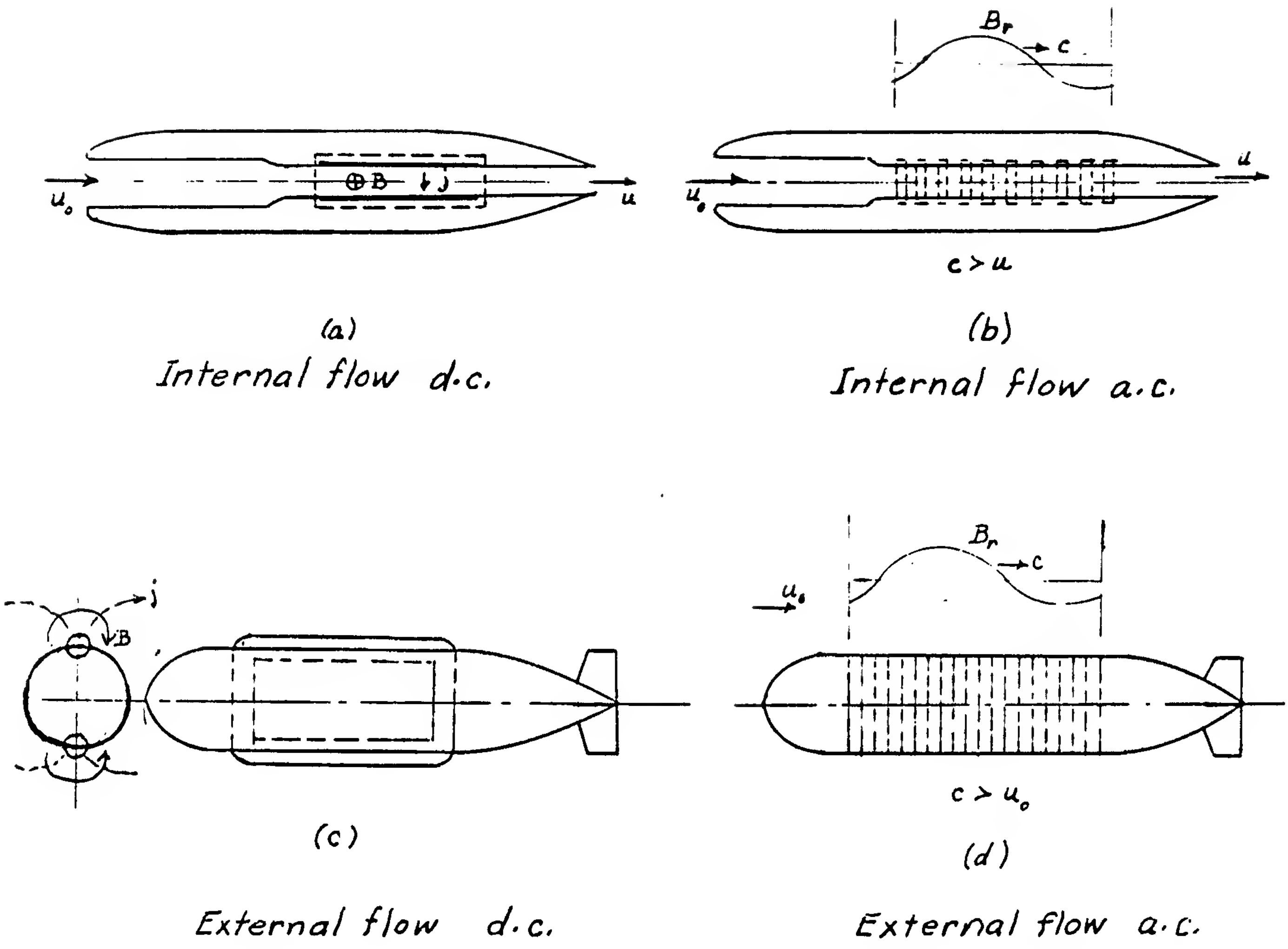


Fig. 1

Alternative electromagnetic propulsion methods.

3. INTERNAL DUCT PROPULSION

How might an electromagnetic pump be applied for submarine propulsion, and what would be the efficiency of such a system in terms of relative duct size, hull drag coefficient, scale factor, cruising speed, sea water conductivity and magnetic field strength, under conditions of thrust = drag?

3. INTERNAL DUCT PROPULSION

A system diagram and the notation used are as follows:

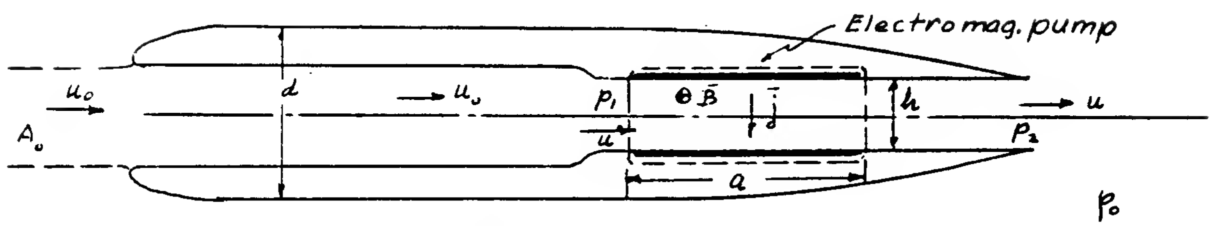


Fig.2

$\bar{B}$ = magnetic induction vector, teslas

B = magnetic induction magnitude, teslas

$\bar{j}$ = current density vector, amps/m^2

j = current density magnitude, amps/m^2

V =potential difference between electrodes, volts

h = width of square channel, meters

a = active duct length, meters

u_o= forward speed, m/sec

u = outlet jet speed, m/sec

p_o= ambient sea pressure, newtons/m^2

p_1= duct inlet pressure, newtons/m^2

p_2= p_o

A_o= approach flow stream tube area, m^2

ρ = sea water density, kg/m^3

σ = sea water conductivity, mhos/m

D = drag force corresponding to external momentum decrement, newt.

F = thrust force corresponding to momentum gain in duct, newt.

C_D= hull drag coefficient based on cross section area πd^2

d = hull diameter, meters

η_j= jet efficiency

η_D= duct propulsion efficiency

η = overall propulsive efficiency

P_L= rate of doing work by Lorentz forces, watts

P_E= electrical power input, watts

P_T= thrust power, watts

For simplicity we assume the device is operating at a condition of inlet velocity ratio equal to unity, that is, the flow speed in the inlet region is equal to the approach speed u_o .

For the inlet region the friction forces are small and we may write the Bernoulli equation:

$$p_o - p_1 = \rho \frac{u_o^2}{2} \left(\frac{u^2}{u_o^2} - 1 \right) \tag{1}$$

The duct outlet pressure p_2 is also equal to p_o . The increase of pressure in the duct depends on the Lorentz force and the frictional drop:

$$p_o - p_1 = jBa - C_f \cdot \rho \frac{u_o^2}{2h} a \tag{2}$$

We also have the current equation and the electric power equation:

$$j = \sigma \left(\frac{V}{h} - u B \right) \tag{3}$$

$$P_E = j V a h \tag{4}$$

Combination of (1) and (2) gives

$$\frac{j}{\sigma uB} = \frac{u_o}{\xi u} \left(\frac{u^2}{u_o^2} - 1 \right) + \frac{C_f}{\xi} \cdot \frac{u_o}{u} \cdot \frac{a}{h} \tag{5}$$

where

$$\xi = \frac{2 a \sigma B^2}{u_o} \tag{6}$$

The latter quantity is the "MHD interaction parameter"; it is a measure of the ratio of Lorentz forces to inertia forces.

The current equation (3) may also be put in the form

$$\frac{j}{\sigma u B} = K - 1 \qquad \text{where} \qquad K = \frac{V}{uBh} \tag{7}$$

We now derive expressions for the various efficiencies. The jet efficiency is the ratio of thrust power to kinetic energy change of the stream. The thrust power is

$$P_T = \rho u h^2 \left(u - u_o \right) u_o = F u_o \tag{8}$$

and we have for η_j

$$\eta_j = \frac{\rho u h^2 (u - u_o) u_o}{\rho \frac{u h^2}{2} (u^2 - u_o^2)} = \frac{2}{1 + \frac{u}{u_o}} \tag{9}$$

The duct efficiency is the ratio of kinetic energy change to electrical power:

$$\eta_D = \frac{\rho u h^2}{2 P_E} \left(u^2 - u_o^2 \right) \tag{10}$$

The propulsive efficiency is the ratio of thrust power to electrical power:

$$\eta = \frac{F u_o}{P_E} = \eta_j \cdot \eta_D \tag{11}$$

The rate of doing work by the Lorentz forces in the duct is

$$P_L = j B h^2 a u \tag{12}$$

and one notes that

$$\frac{P_L}{P_E} = \frac{1}{K} \tag{13}$$

An alternate formulation of η_D is possible by use of (10), (12), (13), (5) and (6):

$$\eta_D = \frac{1}{K} \cdot \frac{1}{1 + C_f \frac{a}{h} \cdot \frac{1}{u^2/u_o^2 - 1}} \tag{14}$$

For negligible friction effects in the duct, $\eta_D = 1/K$

We have finally

$$\eta = \frac{\eta_j}{K \left[1 + C_f \frac{a}{h} \cdot \frac{1}{\frac{u^2}{u_o^2} - 1} \right]} \tag{15}$$

The evaluation of the propulsive efficiency and of other parameters hinges on the value of the speed ratio u/u_o. This ratio is found by equating thrust to drag:

$$\rho \, u \, h^2 \left(u - u_o\right) = \frac{1}{2} \rho \, u_o^2 \cdot \frac{\pi d^2}{4} \cdot C_D \tag{16}$$

This gives

$$\frac{u}{u_o} \left(\frac{u}{u_o} - 1 \right) = \frac{\pi d^2 C_D}{8 h^2} \tag{17}$$

The calculation procedure will now be as follows:

(a) Calculate u/u_o from (17)
(b) Calculate $j/\sigma uB$ from (5) and (6)
(c) Calculate K from (7)
(d) Calculate η_j from (9)
(e) Calculate η_D and η from (14) and (15)
(f) For assumed u_o calculate P_T
(g) Find P_E from (11)
(h) Find j and V from (7). Should check by (4)

For approximate calculations one may take $C_f = 0$

In that case

$$K = 1 + \frac{u_o}{\xi u}\left(\frac{u^2}{u_o^2} - 1\right) \tag{18}$$

$$\eta = \frac{\eta_j}{1 + \frac{u_o}{\xi u}\left(\frac{u^2}{u_o^2} - 1\right)} \tag{19}$$

where u_o/u is to be determined from (17).

Numerical example: (Neglect C_f)

Assume:

$C_D = 0.08$ | $B = 0.1$ tesla
$h = 0.10$ m | $a = 1$ m
$d = 0.50$ m | $u_o = 0.5$ m/sec
$\sigma = 4.5$ mho/m | $\rho = 1030$ kg/m^3

We find:

$\frac{u}{u_o}\left(\frac{u}{u_o} - 1\right) = 0.785$ | $\frac{u}{u_o} = 1.518$
$\eta_j = 0.794$ | $\xi = 0.000175$
$\frac{j}{\sigma uB} = 4910$ | $K = 4911$
$\eta_D = 2.04\times10^{-4}$ | $\eta = 1.62 \times 10^{-4}$
$D = F = 2.02$ newtons | $P_E = 6230$ watts
$P_T = 1.01$ watts | $P_L = 1.272$ watts

$j = 1677$ amps/m^2 | $V = 37.2$ volts

$I = j\,a\,h = 168$ amps | $p_o - p_1 = 168$ newtons/m^2

$\rho\,u\,h^2 = 7.82$ kg/sec | $u = 0.759$ m/sec

It is seen that the efficiency is very low. Since u/u_o depends on drag coefficient and the ratio d/h it will not change appreciably with increasing size, except for the effect of decrease of C_D. However, ξ is directly proportional to size. In the low efficiency range η is nearly proportional to ξ. Another factor that is apparent is that even in large sizes, the efficiency η will still be rather poor unless B is fairly large. To see what conditions must be realized to obtain a reasonably good efficiency of a larger size submarine, suppose we take $C_D = 0.06$ and $d/h = 5$; we then find $u/u_o = 1.416$ and $\eta_j = 0.828$. If η is to be 0.7, a desirable level, we need to have $\xi = 0.388$, by Eq. (19). For this value of ξ, in sea water, we need to have $aB^2/u_o = 44.4$. A reasonable speed of, say, 10 meters/sec, for a duct having a = 20 meters, would require a B field of 4.71 teslas (47100 gauss). This should not lead to discouragement with the concept, however, since such fields are realizable using superconducting materials in the magnet coil. The point to be made here is that large sizes are certainly to be preferred if one wishes to realize good propulsive efficiency with an electromagnetic submarine.

4. TWO POLE EXTERNAL FIELD SYSTEM

How could a bi-polar external field system of electromagnetic propulsion be devised, what would be the field configuration and what would be the propulsive efficiency when thrust = drag, for given hull drag coefficient, electrode geometry, cruising speed, scale factor, sea water conductivity and magnetic field strength?

4. TWO POLE EXTERNAL FIELD SYSTEM

Though we deal here with a two pole system a similar analysis could be carried out for a multipole arrangement, as treated in Ref. 6.

From the standpoint of simplicity the two pole configuration was favored for the Santa Barbara model project. Also, it is shown in Ref. 6 that reducing the number of poles tends to increase propulsive efficiency.

A plan view of a two pole configuration, as it might be installed in a submarine, is shown in Fig. 3.

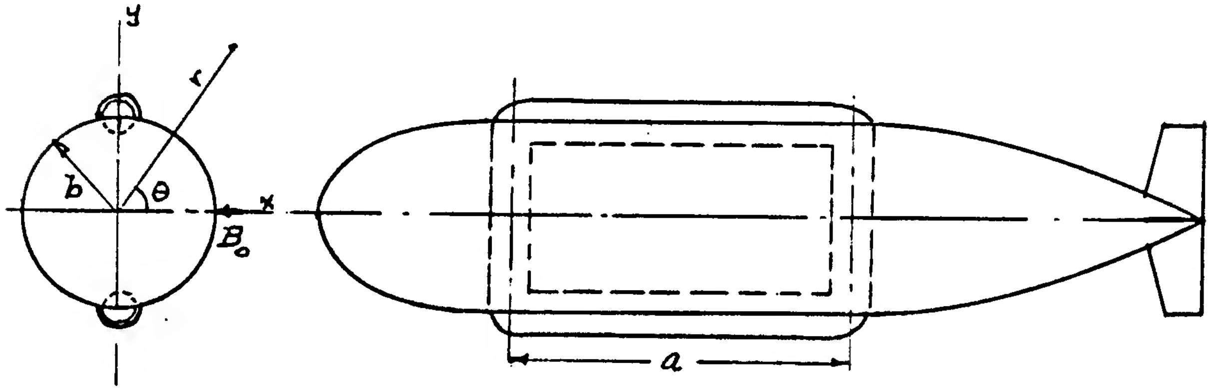
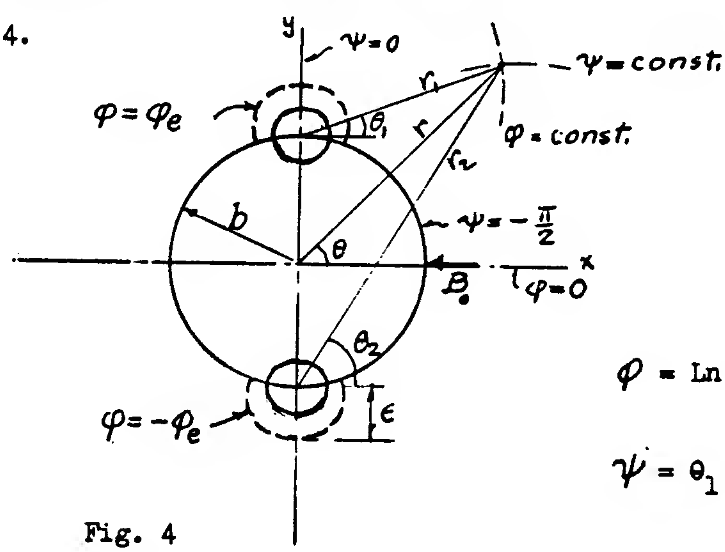


Fig. 3

The notation used in describing the fields is shown in more detail in Fig. 4.



$$\left.\begin{aligned} \varphi &= \ln \frac{r_1}{r_2} \\ \psi &= \theta_1 - \theta_2 \end{aligned}\right\} \qquad (20)$$

Fig. 4

It can be shown by analytic geometry that the curves $\varphi =$ constant are circles with centers on the y - axis, and curves ψ = constant are circles passing through the pole points, with centers on the x - axis. By expressing φ and ψ in terms of x and y it may be shown that the the Cauchy- Rieman equations are satisfied

$$\frac{\partial \varphi}{\partial x} = \frac{\partial \psi}{\partial y} \quad ; \quad \frac{\partial \varphi}{\partial y} = - \frac{\partial \psi}{\partial x} \tag{21}$$

This indicates that the circles of the two families intersect at right angles. Also, φ and ψ will be harmonic functions (satisfying Laplace's equation), and the magnitudes of their gradients are equal:

$$|grad\ \varphi| = |grad\ \psi| = h \tag{22}$$

Parameter h will vary from point to point in the field.

The curvilinear coordinates φ and ψ are also derivable from the analytic function w (ξ) of the complex variable $\xi = x + i\ y$, where

$$\left. \begin{aligned} w(\xi) &= \ln \frac{\xi - i\ b}{\xi + i\ b} \\ w(\xi) &= \varphi + i \psi \end{aligned} \right\} \tag{23}$$

Exciting current may be made to flow in the $-z$ direction (in to diagram) in the exciting conductor centered at x = o, y = b and in the $+z$ direction in the conductor centered at x = o, y = - b. The field at x = b , y = o is then directed to the left. As characteristic field strength we denote the magnetic induction at this point by B_o as shown in Fig. 4.

For preliminary, or simplified, analyses we shall neglect the end effects on the field pattern. The electric current in the sea water, which will be produced by applying a difference of potential across electrodes conformed to surfaces $\varphi = \varphi_e$ and $\varphi = - \varphi_e$, will be assumed to have no z - component. We then know that curl B = 0 everywhere external to the magnet windings, and vestor B can be derived from a magnetic potential. The function

of position ψ meets these requirements, and we can write

$$\bar{B} = C \operatorname{grad} \psi \qquad (24)$$

If we express ψ in terms x and y we have

$$\psi = \tan^{-1} \frac{y - b}{x} - \tan^{-1} \frac{y + b}{x} \qquad (25)$$

The components of gradψ are

$$\frac{\partial \psi}{\partial x} = \frac{b - y}{x^2 + (y-b)^2} + \frac{y + b}{x^2 + (y + b)^2} ; \quad \frac{\partial \psi}{\partial y} = \frac{x}{x^2 + (y-b)^2} - \frac{x}{x^2 + (y+b)^2} \qquad (26)$$

On the x - axis $\frac{\partial \psi}{\partial y} = 0$ and $\frac{\partial \psi}{\partial x} = 2\, b/ (x^2 + b^2)$

Consequently, at the point $x = b$, $= 0$ the gradient of ψ has the components $1/b$ and 0. This determines C, since B_o is the magnitude of $\bar{B}$ at $x = b$, $y = 0$:

$$B_o = C/ b$$

$$C = B_o b$$

The vector $\bar{B}$, and its magnitude B are then

$$\bar{B} = -B_o\, b \operatorname{grad} \psi ; \quad B = B_o\, b\, h \qquad (27)$$

The magnitude of the magnetic induction due to current J in a single straight conductor, at distance r , is $J \mu_o / 2\pi r$ where $\mu_o = 4\pi \times 10^{-7}$ = magnetic permeability of free space. In the bipolar arrangement here treated, the current J in each of the exciting conductors willbe, by reference to Fig. 5 ,

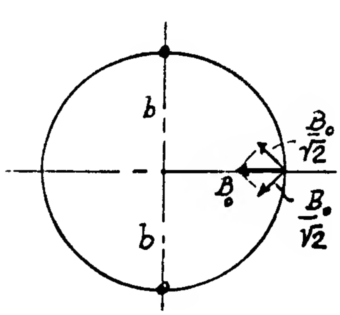


Fig. 5

$$J = \frac{2\pi B_o b}{\mu_o} \qquad (28)$$

Here, as elsewhere in this study, MKS units are employed; J is in amperes. B_o in teslas (webers/m^2) and b in meters. 1 tesla= 10,000 gauss.

The electric field set up in the sea water by the potential difference between electrodes is related to the local potential V by

$$\bar{E} = - \text{grad } V \tag{29}$$

With the possible exception of the regions immediately adjacent to the electrodes there is no space charge in the sea water (it remains electrically neutral) and so div grad V = 0 and V is also a harmonic function. Since its boundary conditions are that it is constant on the surfaces $\varphi = \pm\varphi_e$, the function φ may be used to describe the potential field, V :

$$V = V_e \frac{\varphi}{\varphi_e} \tag{30}$$

Here, V_e is the potential on the electrode surface

The vector $\bar{E}$ and its magnitude E are expressed as

$$\bar{E} = - \frac{V_e}{\varphi_e} \text{grad } \varphi \qquad\qquad E = - \frac{V_e}{\varphi_e} h \tag{31}$$

Parameter φ_e is given by Ln r_{1e} / r_{2e} , or

$$\varphi_e = \text{Ln} \frac{\epsilon}{2b + \epsilon} \tag{32}$$

where ϵ is the height of the electrode shell outwardly from the hull (fig. 6)

Note that φ_e is negative.

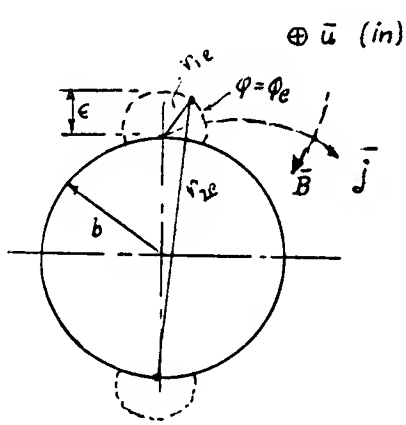


Fig. 6

The current density, $\bar{j}$, depends on the electric field relative to the moving fluid. If $\bar{u}$ is the velocity vector we have

$$\bar{j} = \sigma (\bar{E} + \bar{u} \times \bar{B}) \tag{33}$$

where σ is the electrical conductivity. The applied field $\bar{E}$ is altered by the induced field $\bar{u} \times \bar{B}$.

Since vectors $\bar{u}$, $\bar{B}$, $\bar{E}$ are mutually perpendicular in this case the vector $\bar{u} \times \bar{B}$ will be colinear with $\bar{E}$; however it will be oppositely directed. (If we want the vehicle to be propelled in the forward direction the vector $\bar{j} \times \bar{B}$ must be directed in the same sense as $\bar{u}$; then $\bar{u} \times \bar{B}$ is oppositely directed to $\bar{E}$ and $\bar{j}$). The velocity field in a rather extensive region external to the (nearly cylindrical) middle portion of the hull is nearly uniform, with magnitude u. Since $\bar{B}$ and $\bar{E}$ both have magnitudes proportional to h the vector $\bar{u} \times \bar{B}$ may be expressed as

$$\bar{u} \times \bar{B} = - n \bar{E} \quad ; \qquad n = \frac{uB}{E} \tag{34}$$

and we have the relations:

$$j = \sigma \bar{E} (1 - n) \tag{35}$$

$$j = \sigma E (1 - n) \tag{36}$$

$$j = - \sigma (1 - n) \frac{V_e}{\bar{\varphi}_e} \text{ grad } \varphi \tag{37}$$

$$j = - \sigma (1 - n) V_e \frac{h}{\bar{\varphi}_e} \tag{38}$$

The Lorentz body force per unit volume, $\bar{j} \times \bar{B}$, has magnitude

$$j B = - \sigma (1 - n) \frac{V_e h^2 B_o b}{\varphi_e} \tag{39}$$

The total propulsive force is obtained by integrating j B in the external region, over length a :

$$F = 4 a \int_{-\frac{\pi}{2}}^{o} \int_{\varphi_e}^{o} j B \frac{d\psi \, d\varphi}{h_2} \tag{40}$$

The integration extends over one quadrant, so we must multiply by 4. Note that the element of area is $d\psi \, d\varphi / h^2$. The integration is very simple, in view of (39), and we have

$$F = 2\pi a \sigma b B_o V_e (1 - n) \tag{41}$$

The thrust power is

$$P_t = F u = 2\pi a \ b \ B_o \ V_e u (1 - n) \tag{42}$$

The current flowing around one side of the hull is designated I:

$$I = a \int_b^{\infty} (j)_{y=o} \, dx \tag{43}$$

The value of h on the x - axis is (by 26)

$$(h)_{y=o} = \left| \frac{\partial \psi}{\partial x} \right|_{y=o} = \frac{2b}{x^2 + y^2} \tag{44}$$

Equations (38) and (43) then give

$$I = - \frac{\pi \sigma}{2} (1 - n) \frac{V_e a}{\varphi_e} \tag{45}$$

The total current is 2 I and the total potential difference is 2 V_e so the electric power is

$$P_E = 4 V_e I = - 2\pi\sigma a (1 - n) \frac{V_e^2}{\varphi_e} \tag{46}$$

Quantity φ_e is negative, so P_E is, of course, positive.

In this analysis we are neglecting the alteration of velocity caused by the Lorentz forces. This is an approximation, but closer examination shows that it is a fairly good approximation. The Lorentz forces are of small intensity but act over a large expanse of ocean; thus the velocity change in any stream tube is small.

The propulsive efficiency is the ratio of propulsive power to electric power:

$$\eta = \frac{P_T}{P_E} \tag{47}$$

Substitution gives the following results:

$$n = \frac{u\,B}{E} = -\frac{u\,B_0\,b\,\varphi_e}{V_e} \tag{48}$$

$$\eta = \frac{2\pi a\sigma b\,B_0\,V_e\,u\,(1-n)\varphi_e}{-2\pi a\sigma(1-n)\,V_e^2} = -\frac{u\,B_0\,b\,\varphi_e}{V_e} \tag{49}$$

Thus, parameter **n** also is equivalent to propulsive efficiency. This comes about because n is the ratio of Lorentz force work rate to electrical power, and since we have here no high speed slip stream, the " jet efficiency " is unity, and propulsive power and Lorentz power are alike.

A meaningful evaluation of propulsive efficiency, for practical applications, requires that the voltage V_e be high enough to drive sufficient current through the sea water to make thrust = drag. The drag is

$$D = \tfrac{1}{2}\rho u^2 . \pi b^2 . C_D \tag{50}$$

and the condition F = D gives (with $n = \eta$)

$$2\pi a\,b\sigma B_0\,V_e\,(1-\eta) = \tfrac{1}{2}\rho u^2 . \pi b^2\,C_D$$

$$\therefore\quad V_e = \frac{\rho\,u^2 b\,C_D}{4\,a\sigma B_0\,(1-\eta)} \tag{51}$$

Substitution from (48) and solution for η now gives

$$\eta = \frac{1}{1 - \dfrac{C_D}{2\xi\varphi_e}} \quad ; \qquad \xi = \frac{2\,a\sigma B_0^2}{\rho\,u} \tag{52}$$

Numerical example: Note, this example is based on assumed use of a superconducting magnet, so the field B_0 is taken rather high. We will

not be concerned with the problems of magnet design and construction, as the example is intended only to illustrate use of the relations developed above.

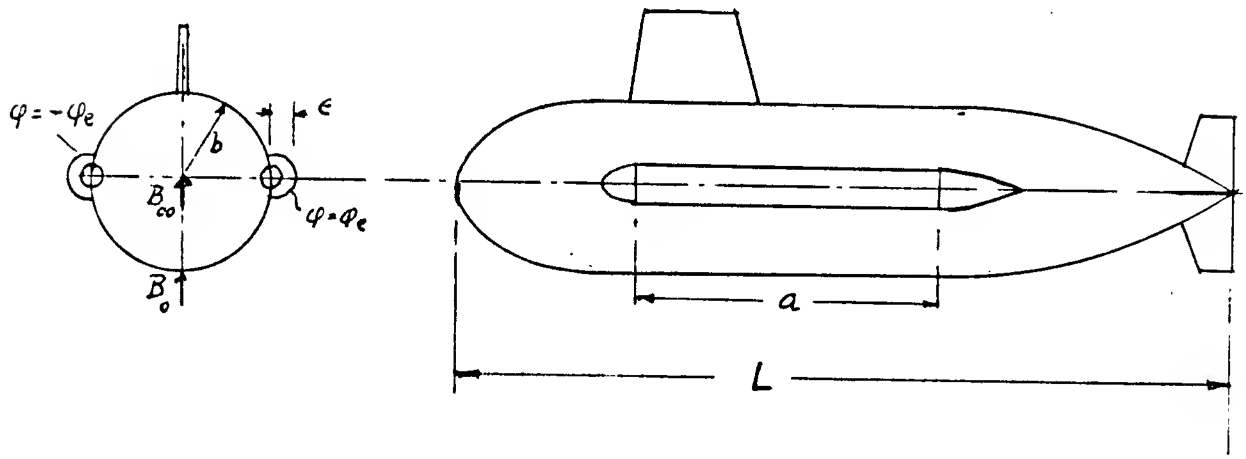


Fig.7

Assumed data:

$C_D = 0.06$	$B_o = 1.0$	$u = 2, 4, 8$ m/sec
$L = 20$ m	$\epsilon = 0.5$ m	
$a = 10$ m	$\sigma = 4.5$ mho/m	
$b = 2$ m	$\rho = 1030$ kg/ m^3	

Results:

$$\xi = \frac{0.0873}{u}$$

$$\frac{C_D}{2\xi\varphi_e} = -0.1564\ u \qquad \varphi_e = \text{Ln}\ \frac{0.5}{4.5} = \text{Ln}\ 0.1111 = -2.197$$

$$D = 389\ u^2\ ; \qquad \eta = \frac{1}{1 + 0.1564\ u}$$

$$P_T = 389\ u^3 \qquad P_E = P_T / \eta$$

$$2\ V_e = \frac{-2u\ B_o b \varphi_e}{\eta} = 8.788\ \frac{u}{\eta}\ ; \qquad 2\ I = \frac{P_E}{2\ V_e}$$

u , m/sec	2	4	8
D , newtons	1556	6230	24,860
P_T, watts	3112	24900	199,000
η	0.762	0.615	0.444
P_E, watts	4080	40500	448000
2 V_e, volts	23.1	57.1	158
2 I, amps	176.5	709	2840

5. OPTIMUM ELECTROMAGNETS

The problem is presented of identifying the conditions for a rectangular coil electromagnet design (no iron) that will lead to the lowest total weight of the magnet and batteries to operate it, while producing a field of specified strength.

5. OPTIMUM ELECTROMAGNETS

In comparing internal and external flow configurations it was necessary for the design group to look at optimum magnets in both cases. In either case a generally rectangular coil configuration is used. One can either use a large amount of metal with low power for excitation, or a more compact exciting conductor with larger power for excitation.

The problem is to identify the conditions for a rectangular coil electromagnet design that will lead to lowest total weight of magnet and batteries to operate it.

A coil ofthe configuration considered is shown in Figure 8.

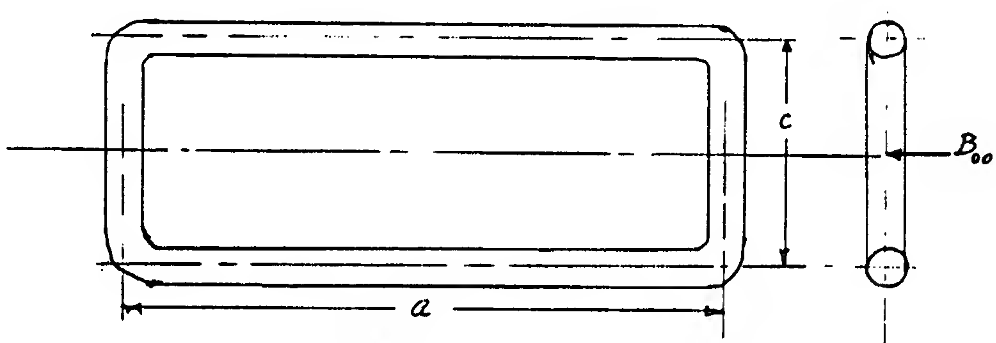


Fig. 8

Let ρ_m = density of metal in coil

A_m = total cross section of metal carrying current

β = a/c

ω = metal resistivity

τ = desired running time

k = watt hrs/ kg in batteries, for time τ.

W_m = mass of magnet coil

W_{mB} = mass of magnet battery

W_s = mass of magnet system = $W_m + W_{mB}$

J = total current in coil (ampere turns)

R_m = magnet coil resistance, regarded as single turn.

$\mu_o = 4\pi \times 10^{-7}$ permeability of free space

P_m = magnet excitation power, watts

Magnet mass: $W_m = 2\,c\,(1+\beta)\,A_m\,\rho_m$

Exciting current: $J = \dfrac{\pi c\, B_{oo}}{2\mu_o}$ amps

Magnet coil resistance: $= R_m = \dfrac{2\,c\,(1+\beta)\,\omega}{A_m}$

Magnet power: $P_m = J^2 R_m = \left(\dfrac{\pi c\, B_{oo}}{2\mu_o}\right)^2 \cdot \dfrac{2c\,(1+\beta)\,\omega}{A_m}$

Battery mass: $W_{mB} = \dfrac{P_m \tau}{k}$

System mass: $W_s = W_m + W_{m\,B}$

We find therefore

$$W_s = 2\,c\,(1+\beta)\,A_m\,\rho_m + \left(\frac{\pi c^2 B_{oo}}{2\mu_o}\right)^2 \cdot \frac{2\,(1+\beta)\,\omega}{c\,A_m} \tag{53}$$

Let $y = c\,A_m$

$$W_s = C_1\,y + \frac{C_2}{y} \tag{54}$$

$$C_1 = 2\,(1+\beta)\,\rho_m$$
$$C_2 = \left(\frac{\pi c^2 B_{oo}}{2\mu_o}\right)^2 \cdot 2\,(1+\beta)\,\omega$$

Optimization:

$$\frac{d\,W_s}{d\,y} = 0$$

$$C_1 - \frac{C_2}{y^2} = 0$$

Denote optimum values by (*) :

$$y^* = \sqrt{\frac{C_2}{C_1}} \tag{55}$$

$$y^* = c\,A_m^* = \frac{\pi c^2 B_{oo}}{2\mu_o}\sqrt{\frac{\omega\tau}{k\rho_m}} \tag{56}$$

We note that $C_1\,y^* = C_2/y^*$ and hence $W_m^* = W_{mB}^*$; for optimum conditions the mass of the magnet coil and the mass of the magnet battery are equal. This is true regardless of the values of ω, ρ_m, τ or k.

The masses W_m^* and W_{mB}^* are

$$W_m^* = W_{mB}^* = 2\,(1+\beta)\,\rho_m\,y^* \quad (57)$$

$$\rho_m y^* = \frac{\pi c^2 B_{oo}}{2\mu_o}\sqrt{\frac{\rho_m \omega \tau}{k}} \quad (58)$$

It was necessary to make a decision as to the best material to use for the magnet. The best material (without regard to cost) would be that for which the product $\rho_m \omega$ is minimum. The following figures were compiled from the Handbook of Chemistry and Physics: (Assumed temp. 20° C).

	Copper	Aluminum	Silver	Magnesium
ρ_m, kg/m^3	8900	2700	10500	1740
ω ohm m	$1.724\text{x}\ 10^{-8}$	$2.82\text{x}\ 10^{-8}$	$1.59\text{x}10^{-8}$	$4.60\text{x}\ 10^{-8}$
$\rho_m \omega$	$15.35\text{x}\ 10^{-5}$	$7.62\text{x}\ 10^{-5}$	$16.7\text{x}\ 10^{-5}$	$8.00 \text{ x } 10^{-5}$

Aluminum or magnesium would be superior to copper, by quite a considerable amount of weight reduction. Fortunately, aluminum conductors can be purchased and the cost is reasonable.

There was found to be one practical disadvantage to aluminum in this project ; the space required for the coil is larger than in the case of copper, and the electrodes must be made of larger dimensions. This reduces the φ_e parameter and reduces efficiency. However, the low weight W_s^* and the relative availability of aluminum wire were attractive considerations. Actually, the main portion of the coils was made of No. 4 aluminum wire, and a smaller amount of No. 12 copper was added to "trim" the coil to the desired number of ampere turns.

6. COMPARISON OF INTERNAL AND EXTERNAL DUCT FLOW SYSTEMS

In designing the model electromagnetically propelled submarine a decision had to be made regarding the merits of the internal flow system with electromagnetic pump, or an external field propulsion system. On what basis should such a comparison and decision be based, and what quantitative conclusions can be drawn in favor of one course or the other?

6. COMPARISON OF INTERNAL AND EXTERNAL FLOW SYSTEMS

It was necessary to decide whether to use an internal duct arrangement or an external field arrangement.

To make the comparison, optimum designs have to be examined for each system. The optimizations should be made on the basis of minimum weight of magnet, plus magnet battery, plus propulsion battery. The same hull size, L = 3 m and 2 b = 0.45 m, is assumed in both cases (internal and external flow) and the cruising speed isassumed at the reasonable value of 0.5 meters/sec. The drag coefficient based on hull cross section is taken as $C_D = 0.09$.

a) <u>External flow.</u> (Ref. Eq. 52)

$$\xi = \frac{2\, a\, \sigma\, B_o^2}{\rho\, u}$$

The reasonable value of "a" for the 3 meter hull is a = 1 m. If we take $\sigma = 4.5$ mhos/m, $\rho = 1030$ kg/m^3 and u = 0.5 m/sec we have $\xi = 0.0175 B_o^2$. In the effficiency expression, Eq. 52, the second term in the denominator is large compared to unity and we may write

$$\eta = -2 \cdot \frac{\xi\, \varphi_e}{C_D}$$

It is anticipated that electrode height ϵ will be about 0.08 m, and with b = 0.225 m we find (see Fig. 9)

$$\varphi_e = \mathrm{Ln}\ \frac{0.08}{0.45 + 0.08} = -1.892$$

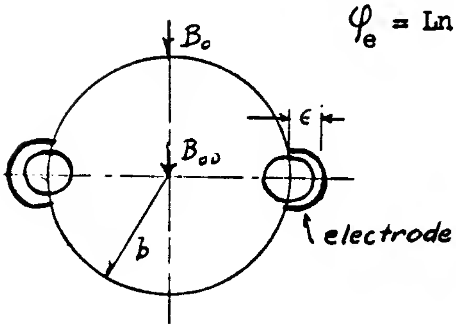


Fig. 9

We thus obtain

$$\eta = 0.735\ B_o^2$$

Thrust power will be

$$P_T = \frac{1}{2}\rho u^2 \cdot \pi b^2 \cdot C_D \cdot u = 0.923 \text{ watts}$$

and the drag is

$$D = 1.846 \text{ newtons}$$

Electric power is

$$P_E = \frac{P_T}{\eta} = \frac{1.255}{B_o^2}$$

Mass of propulsion battery:

$$W_{PB} = P_E \frac{\tau}{k} = \frac{1.255\tau}{B_o^2 k} \tag{59}$$

Mass of magnet plus magnet battery for optimum design:

$$W_m^* + W_{m\,B}^* = 4\,(1+\beta)\left(\frac{\pi\, c^2 B_o}{\mu_o}\right)\sqrt{\frac{\rho_m \omega \tau}{k}} \tag{60}$$

Here we make use of Eqs. 57 and 58 but note that B_o at the top (or bottom) of the hull is just 0.5 B_{oo}, where B_{oo} is at the center point.

The total of the three masses is

$$W = W_{PB} + W_m^* + W_{m\,B}^* = \frac{c_1}{B_o^2} + c_2\,B_o \tag{61}$$

where

$$c_1 = \frac{1.255\,\tau}{k} \qquad\qquad c_2 = 4\,(1+\beta)\left(\frac{\pi c^2}{\mu_o}\right)\sqrt{\frac{\rho_m \omega \tau}{k}}$$

If one sets $dW/dB_o = 0$ to find the optimum B_o value the result is

$$B_o^* = \left(\frac{2c_1}{c_2}\right)^{1/3} \tag{62}$$

Substitution shows that the optimum values of W_{PB}, W_m and $W_{m\,B}$ are equal:

$$W_{P\,B}^* = W_m^* = W_{m\,B}^* \tag{63}$$

The power of the propulsion battery should equal the power of the magnet battery.

The optimum magnetic field is thus, for the previously assumed values of ρ , u, σ, b, a and C_D :

$$B_o^* = \left[\frac{2.51\tau}{k} \cdot \frac{\mu_o}{4\ (1+\beta)\,\pi\, c^2 \sqrt{\rho_m \tau \omega / k}}\right]^{1/3} \tag{64}$$

If we insert in (64) the numerical values

$\tau = \frac{1}{3}$ hr. , k = 15 watt hrs/ kg , $\mu_o = 4\pi \times 10^{-7}$, $\beta = 2.22$, c = 0.45

ρ_m = 2700 kg / m^3 , ω = 2.82 x 10^{-8} ohm m , $\tau/k = 1/45$

we find

B_o^* = 0.0187 teslas (187 gauss)

η = 0.000 256

$W^*_{P\,B}$ = 79.8 kg = W^*_m = $W^*_{m\,B}$

Total propulsion system mass is

W = 239 kg.

(b) Internal flow

The largest reasonable size for the internal duct is assumed to be a square of side b/2 , and the center distance of the magnet exciters is taken as b . See Fig.10. The assumption is here made that the field in

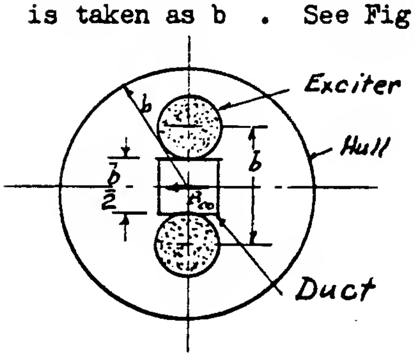


Fig.10

the duct may be treated as uniform, of value B_{oo} .

Now u/ u_o , by Eq. 17, satisfies the relation:

$$C_D = 2\frac{A_D}{A}\ \frac{u}{u_o}\left(\frac{u}{u_o} - 1\right) \tag{65}$$

where $A_D = b^2/4$ and $A = \pi b^2$

With $C_D = 0.09$ as before we find $u/u_o = 1.40$. By application of (9) and (19) one finds

$$\eta = \frac{0.833}{1 + 0.693/\xi}$$

In this case, assuming length of the duct a = 1 meter,

$$\xi = \frac{2\, a\, \sigma B_{oo}^2}{\rho u_o} = \frac{9 \times 1 \times B_{oo}^2}{1030 \times 0.5} = 0.01746\, B_{oo}^2$$

$$\eta = 0.0295\, B_{oo}^2$$

$$P_E = \frac{44}{B_{oo}^2}$$

$$W_{PB} = \frac{44}{B_{oo}^2} \cdot \frac{\tau}{k}$$

$$W = \frac{c_1}{B^2} + c_2 B_{oo}$$

The c_1 and c_2 values are

$$c_1 = \frac{44\,\tau}{k} \quad ; \quad c_2 = 4\,(1+\beta)\,\frac{\pi c^2}{2\mu_o}\sqrt{\rho_m \tau\omega/k}$$

Here, again the optimum field will be

$$B_{oo}^* = \left(\frac{2c_1}{c_2}\right)^{1/3}$$

and for $\tau/k = 1/45$ and $\beta = a/b = 4.445$, $c = b = 0.225$

and other parameters as assumed in the external flow case,

$$B_{oo}^* = 0.1028 \text{ tesla}, \quad (1028 \text{ gauss})$$

We find also

$$\eta = 0.000221$$

$$W_{PB}^* = 92.7 \text{ kg} = W_{m\,B}^* = W_m^*$$

Consequently the propulsion system mass is

$$W = 278 \text{ kg}$$

This is 39 kg heavier than in the external flow case. One therefore is led to favor an external flow design.

7. PROPULSION CALCULATIONS AT DESIGN CONDITIONS

For a model of the appropriate size (3 meters long , about 0.45 meters dia., and active field length a = 1 meter) what is the appropriate design cruising speed, what is the best magnetic field strength and what will be the other parameters at the design condition such as efficiency, electric power, drag force, thrust power, battery and magnet weights, voltage, electrode current and magnet current?

7. PROPULSION CALCULATIONS AT THE DESIGN CONDITIONS

Having ascertained that an external field configuration could probably be built to give better performance than an internal duct configuration, the next step to be taken was to determine the parameters of the propulsion system.

Several of the principal dimensions were already fairly well established at this point:

$$L = 3 \text{ meters}$$

$$2b = 0.45 \text{ meters}$$

$$a = 1.0 \text{ meter}$$

Some consideration had been given to the idea of reducing all these dimensions by $\frac{1}{2}$, and accepting the inferior performance that would result. The reason for entertaining this idea was the shortage of time available. However, enthusiasm for the larger model prevailed, and the design study was continued for the 3 meter submarine.

A profile view of the hull, as initially visualized is shown in Fig. 11.

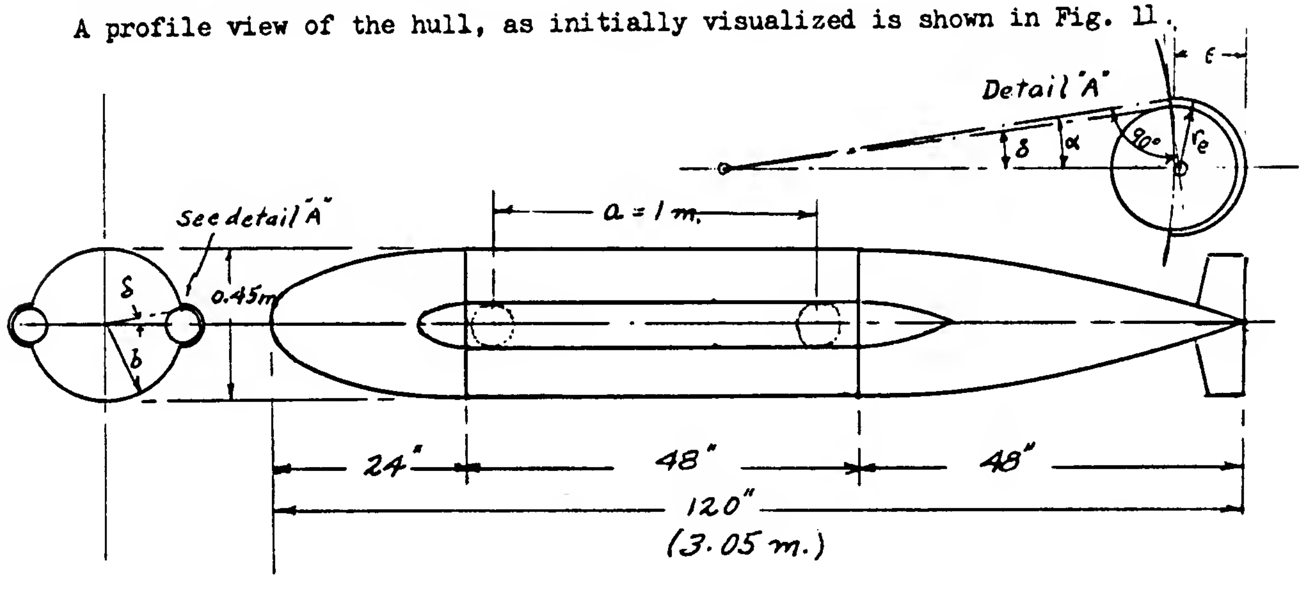


Fig. 11

The hull design team after consulting reference materials and carrying and on some correspondence with a cooperative naval architect, decided upon

a hull configuration with the following offset dimensions:

x	inches	0	6	12	24	72	84	96	108	120
y	inches	0	12.3	16.0	17.69	17.69	16.61	12.80	7.12	0

A drag coefficient for such a body, with some allowance for empenage drag was estimated to be about $C_D = 0.09$, based on hull cross section area. The $L/2b$ ratio of 6.78 is not far from optimum.

The electrode radius r_e (see Fig. 10) was selected on a trial basis, at what looked like a reasonable value. Some preliminary calculations on the basis of the trial value indicated it would probably be suitable. The value used was $r_e = 0.068$ m. This is based on a magnet winding radius (for the bundle of wires) of 6 cm. with a multiplier of 1.1 to allow for spacing between electrode face and magnet winding*. The value of φ_e for this electrode geometry is -1.914, and electrode height becomes 0.0779 m.

A preliminary calculation at an assumed speed of $u = 0.42$ m/sec and drag coefficient $C_D = 0.08$ disclosed that acceptable magnet and battery weights could be realized. However, it was felt that a more conservative C_D value should be used. With $C_D = 0.09$, the assumed running speed was dropped to 0.40.

Instead of calculating the optimum B_o value, by Eq. 64 (which at that time had not been discussed in the group) the power and weight calculations were made for several assumed B_o values. For each B_o the optimum magnet winding is used, in accord with the equations of Section 5.

* The geometrical calculation is illustrated in Fig. 11. We assume $\alpha = 1.1\,\delta$ and $0.06 = b\delta$, so $\delta = 0.0267$; $\alpha = 0.2935$. Hence $\varphi_e = \ln \tan \alpha/2 = -1.914$ and $r_e = b \tan\alpha = 0.0681$ m. From the relation $\epsilon/(2b + \epsilon) = \tan \alpha/2$ we find $\epsilon = 0.0779$ m.

Parameters used in calculating the optimum amount of wire in the magnet were based on the density ρ_m' and resistivity ω' associated with wire + insulation + void. The assumption was to be made the wire to be used was "pear" type polyethylene covered aluminum (Aluminum Co. of America designation), for which:

wire gauge no. 4

metal diam. = 0.2043 in.

dia. over insulation = 0.267 in.

For closely packed turns the density ρ_m' in the complete winding is calculated to be 1829 kg/ m^3. The resistivity ω' of the coil composite (considering metal, insulation and void), is 5.30×10^{-8} ohm meters. In terms of B_o (instead of B_{oo}) we have, by Eq. 56,

$$y^* = 2\,b\,A_m^* = \frac{\pi\,(2b)^2 B_o}{\mu_o}\sqrt{\frac{\omega'\,\tau}{k\,\rho_m'}} \tag{66}$$

Also, the mass of the magnet winding, as well as of the magnet battery, is

$$W_m = W_{mB} = 2\left(1 + \frac{a}{2\,b}\right)\rho_m'\,y^* \tag{67}$$

For the design calculation we assume $\tau = 1/3$ hr. operation and $k = 15$ watt hrs / kg. (The latter value subsequently was found to be overly optimistic). On this basis one finds

$$A_m^* = 0.903\ B_o$$

$$W_m = W_{mB} = 4780\ B_o$$

The diameter of the magnet winding would be

$$d_m^* = \sqrt{\frac{4A_m^*}{\pi}}$$

We may now see how the calculations turn out for various assumed B_o values. Conductivity was assumed at 4 mhos/m.

$$D = \frac{1}{2} \rho u^2 \cdot \pi b^2 \cdot C_D = 1.18 \text{ newtons.}$$

$$P_T = 0.472 \text{ watts}$$

$$\xi = \frac{2 a \sigma B_o^2}{\rho u} = 0.0194 B_o^2$$

The efficiency is , for cases such as we have in this design

$$\eta \cong -\frac{2 \xi \varphi_e}{C_D} \tag{67}$$

or

$$\eta = 0.827 B_o^2$$

We will have $P_E = P_T / \eta$ and $W_{PB} = P_E / 45$ by Eq. 59.

The battery power drawn by the magnet is simply $P_m = 45 W_m$.

The results for various B_o values are

B_o ,teslas	0.010	0.015	0.020
$1/n$	12100	5380	3025
$10^6 \xi$	1.94	4.37	7.76
P_E,(watts)	5720	2540	1440
W_{PB} kg	127.2	56.4	32.0
A^*, m^2	0.00903	0.01355	0.01808
W_m,kg	47.8	71.7	95.6
W_{mB} , kg	47.8	71.7	95.6
d_m^*	0.107	0.131	0.152
$W_s = W_{PB} + W_m + W_{mB}$,kg	222.8	199.8	223.2
P_m , watts	2150	3230	4310

Though the optimum point for minimum propulsion system mass might have been with B_o slightly less than 0.015 teslas, the value 0.015 was adopted as the design value. One reason for doing this was that the required voltage tends to rise if smaller B_o is used, since, then, a larger current must be sent through the sea water to obtain the desired thrust. The voltage is calculated by combination of (48) and (67):

$$2\ V_e = -\ \frac{2\ u\ B_o\ b\ \varphi_e}{\eta} = \frac{0.417}{B_o}$$

In our previous notation the current from the anode was $2I$; we shall now use the notation I_p for this " propulsion " current, and I_m for the magnet current. The total ampere twins for the magnet, designated J_m, is

$$J_m = \frac{2\pi b\ B_o}{\mu_o} = 0.1125\ B_o \times 10^7$$

If we connect the magnet circuit and electrode circuit in parallel the voltage $2\ V_e$ will be common to both and the magnet current I_m is $P_m / 2V_e$.

Results for $2\ V_e$, I_p, I_m and J_m below:

		↓	
B_o	0.010	0.015	0.020
$2\ V_e$	41.7	27.8	20.85
I_p	137	91.4	69.1
I_m	51.5	116.3	207
$I_p + I_m$	188	208	276
J_m	11250	16900	22500

If we contemplate using lead-acid storage batteries the B_o value 0.015 tesla is appropriate, because 5 six-volt batteries will have close to 27 volts while delivering current. Columns with arrows at the top (↓) give the design values for the model.

8. ELECTRICAL SYSTEM DESIGN

What type of battery might best be used, what cruising time (discharge time) should be assumed, what type and legnths of wire should be used to construct the magnet, and what is the electrical system wiring diagram? Also, how can one easily check electrical conductivity of the sea water?

It will be seen that the bundle of magnet wire at $B_o = 0.015$ has a diameter $d^* = 0.131$ meters, which is slightly higher than the 0.12 meters chosen at the outset as a plausible value. However, since the electrode diameter is 0.136 meters it was felt that the d_m^* value of 0.131 might be acceptable. (It will be seen later how this decision led to certain difficulties).

8. ELECTRICAL SYSTEM DESIGN

The propulsion system group included one man who was con-concerned chiefly with magnet design and optimization, one man who was specializing in the field theory and examining current and voltage requirements, a man who was looking into energy sources (storage batteries) and a man concerned with the design of the actual circuitry, switches, electrodes, battery installation, etc. All these individuals had to constantly keep in touch and be aware of what each other was doing.

In regard to battery selection, contacts were made with representatives of the Yardney Battery Company on Ag - Cd or Ag - Zn cells, and with Dr. Himi*, who generously gave of his time to discuss battery problems with the group. Also Mr. Raymond Godber of the Trojan Battery Company and Mr. Walter Burdick of Burdick Battery and Electric Company, Santa Barbara, contributed helpful information on lead-acid battery characteristics.

Silver-cadmium and silver-zinc batteries, while having advantages of considerably higher watt hours/lb than lead-acid batteries, are so extraordinarily costly that they had to be immediately ruled out for the submarine model.

Comparison of lead-acid batteries with nickel-cadmium is nearly a stand-off, performance-wise, but for the same energy release the cost of Ni - Cd batteries is several times higher than for lead acid. Ni - Cd batteries also take up more space than lead-acid, on account of the lower voltage per cell, approx 1.2 as compared to 2 volts.

Lead acid batteries of the type used in golf carts have been developed to give good output with light weight. The Trojan J-217 battery delivers 217 a. h. on an 8 hour discharge basis. Other characteristics of this

* Douglas Aircraft Company

battery are as follows:

No. of cells	3
length	10 3/8"
width	7 1/16"
height	10 1/4"
weight incl. electrolyte	69 lbs.
O. C. voltage/cell	2.1 volts
nominal w. h./ lb. (8 hr. disch.)	19.8

Current vs. discharge time:

75 a. for 103 min.	(9.9 w. h. /lb.)
205 a. for 21 min.	(5.5 w. h. / lb.)

205 ampere test:

Time	Voltage
5 sec	5.45
30 sec	5.40
5 min	5.39
8 min	5.32
10 min	5.30
12 min	5.25
15 min	5.20
16 min	5.20
17 min	5.19
18 min	5.15
19 min	5.12
20 min	5.11
21 min	5.10

Since it was anticipated that the current demand in the submarine would be 208 amps, we would anticipate a running time of about 20 minutes before the batteries were exhausted*. Voltage during the main part of the run (up to 5 minutes) would be about 5.4 volts per 3- cell battery;

* The assumption of any longer running time than 20 minutes for τ in the foregoing design analysis would have led to excessively heavy batteries and magnet.

for 5 such batteries the voltage during discharge is 27 volts which compares with the "design" value of 27.8. This was considered satisfactory.

An additional point of interest was that Mr. Godber reported that a J - 217 battery on test delivered 300 amps for 14 minutes before voltage decline.

Five J - 217 batteries willweigh 345 lbs or 156 kg. In this respect the design value is exceeded , as $W_{mB} + W_{PB}$ in the design tabulation in Section 7 was 128 kg. This was due to the fact that our assumed value of 15 watt hrs/kg is not realized; actual value is about 12 watt hrs/ kg. at the 21 minute discharge rate.

The space requirement of the five J - 217 batteries is (allowing 1/8" clearances between calls): length= 35 $\frac{3}{4}$" , width = 10 5/8" , height = 10 $\frac{1}{4}$". Actually several inches above the actual battery height should be available to allow space for connections and cables. This amount of battery space is available in the center section, and installation may be made through a hatch at the top. Battery racks of " Aim " Brand 225 slotted angle were fabricated; the batteries are fastened in place with center of gravity 1.9" below the hull center line.

The magnet coil design involved a few compromises and it is instructive to review the situation.

The desired ampere turns were 16900, and the desired current was 116.3 amps at 27.8 volts. However, the battery will probably only have 26.5 volts while delivering full current. We retained the figure of 116.3 amps as desired current in the magnet circuit, as a basis for further design. The number of coil turns would be 16900 / 116.3 or 145 turns. In passing we note that the mean length per turn is 2 (1 + 0.45), or 2.90 meters, so the total length with 145 turns would be 420 meters.

No. 4 aluminum wire has a resistance of 0.001338 ohms per meter. With 26.5 volts and 116.3 amps the circuit resistance should be 0.228 ohms,

and, for length 420 meters, 0.000543 ohms/meter. Hence 2.46 wires (No.4) would give the required current and resistance. Of course an integral number of wires must be used; a single No. 0 wire (8.3 m m dia) or two No. 3 wires (5.8 m m dia) could be used to give the desired 0.000543 ohms/meter. The No. 0 wire would be too stiff to handle; the No. 3 wire was not available. No. 4 wire was available , so something had to be done about combination of an auxilliary winding along with 2 strands of No. 4.

A further complication arose from the fact that the length in the standard coil was 2550 feet, or 777 meters, instead of 840 meters as would be necessary for the 145 double turns.

A compromise therefore had to be made. The compromise was in the direction of increasing power consumption rather than reducing performance.

The magnet coil design was finally arrived at in the following manner, taking account of the above mentioned restraints. Using double turns of 388 meters, approximately 134 turns can be applied of 2.9 meters mean length per turn. The current to be carried is then 16900/ 134 or 126.3 amps. At 26.5 volts, each 388 meter strand of No. 4 aluminum wire, of resistance 0.001338 ohms/meter, will carry 51 amps. The two parallel wires carry 102 amps. The additional 24.3 amps must be carried by the additional winding. If that winding also consists of 134 turns for a total of 388 meters length, the resistance will be 1.09 ohms, or 0.00281 ohms/meter. Such a wire, in aluminum would fall between sizes 7 and 8 (Amer. wire gauge); in copper it would be a wire between No. 9 and No. 10. No. 10 copper at 20° C has resistance 0.00328 ohms/meter. It would be considered satisfactory to use 388 meters (134 turns) of No. 10 wire. The amperes carried in the auxilliary winding would be 20.8 amps; total ampere turns would consist of* :

* To the best of the writer's collection, No. 12 wire was used in place of No. 10. This would reduce the total ampere turns to 15400.

2 aluminum No. 4 wires	13680	a. turns
1 copper wire No. 10	2790	a. turns
Total	16470	a. turns

The auxilliary winding of copper was wound between the first aluminum winding and the second, so that it would have the desired 134 turns with 388 meters of wire.

The electrodes consisted of sections of 6" O.D. x 1/8" wall aluminum tubing, approx. 47" long, cut lengthwise so as to form a cylindrical half shell enveloping the magnet winding. Closures were made at the ends, and fairings of balsa wood*served to stream-line the fore and aft termination of the electrode structures.

The electrical circuit is shown in Fig. 12. Main battery leads were taken to rigidly fixed terminal points (binding posts) on a small panel. From there, conductors carried the current to the two main busses running up the mast. A meter and switch box was located at the top of the mast as shown in Fig. 17. The main busses first went through a double pole, single throw switch. The negative lead then returned through the mast, and was connected, via a terminal board, to the port electrode and the three magnet coil return leads. The positive lead, beyond the switch, divides into two continuing conductors. The first + lead goes through an ammeter and thence down the mast to the terminal board and magnet windings (current input connection to magnet). The second + lead goes through a second ammeter and thence down the mast to the terminal board, and from there to the starboard electrode. A voltmeter wasplaced across the far terminals of the double pole switch.

Current flows in the magnet coil clockwise as viewed from the top.

* Styrafoam, glass-plastic coated, in alternate design.

The conductors inside the mast consisted of three copper strips, about 1/8x5/8 and two about 1/8x3/8 for the positive return leads. These strips were insulated from one another and from the enclosing tube, which was 1.05"O.D. with o.113" wall. (Some rounding of edges was done to give added clearance and accomodate insulating tape). Battery leads were of heavy flexible copper cable. Sizes of all leads were selected with appropiate consideration of voltage drops under the anticipated high currents, such combined potential drops being of the order of 1 to 1.5 volts.

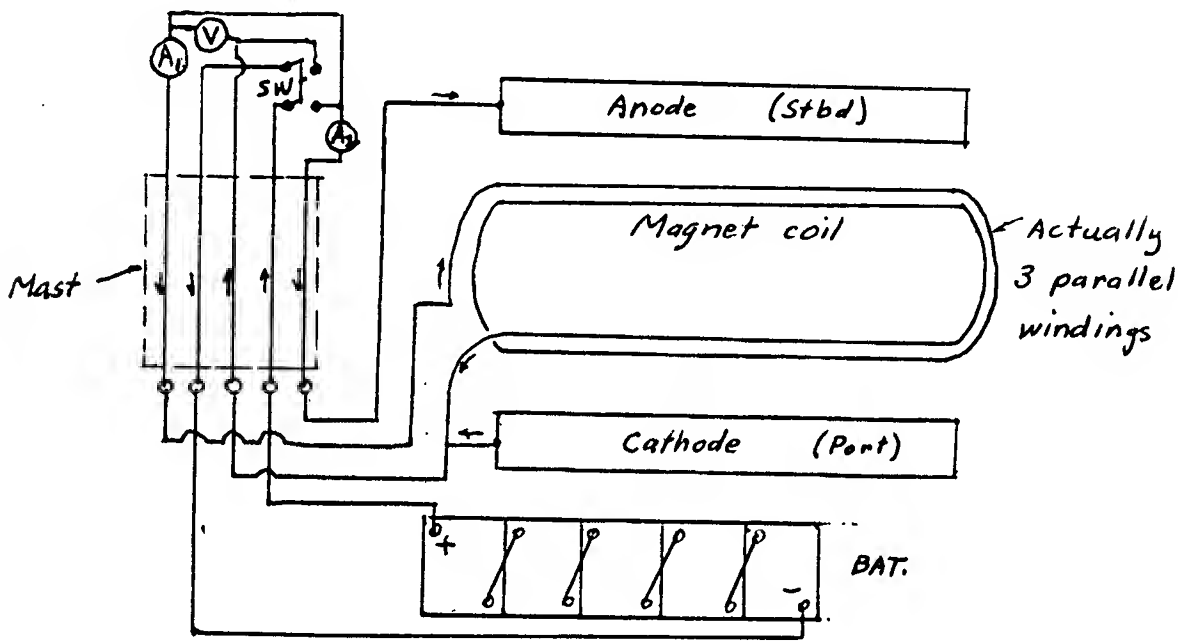


Fig. 12

SW - DPST shop built mercury switch.

V - Type MM 15 K-116 Weston 301 DC volt meter 0- 50 V.

A_1 , A_2 - Type MM 9026 Westinghouse 0.300 D.C. ammeter with shunts.

BAT - 5 storage cells - 6 volt- 217 a. h. Trojan J-217.

Several questions arose relating to the conduction of current in the sea water. First of all, to ascertain the conductivity (4 mhos/meter had been assumed in the design calculations) a side experiment was made as shown in Fig. 13 .

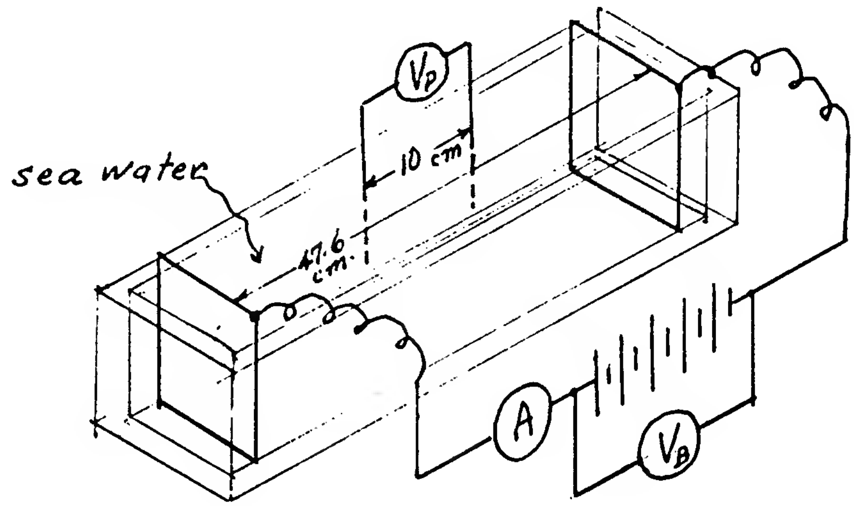


Fig. 13

The plastic box was filled with sea water at room temperature (66°F). The separation distance of the electrodes was 47.6 cm. The probe separation distance was 10 cm. Cross section area of the prismatic body of water was $A = 0.00795\ m^2$. The voltage pattern at a current of 1.25 amps was as shown in Fig. 14.

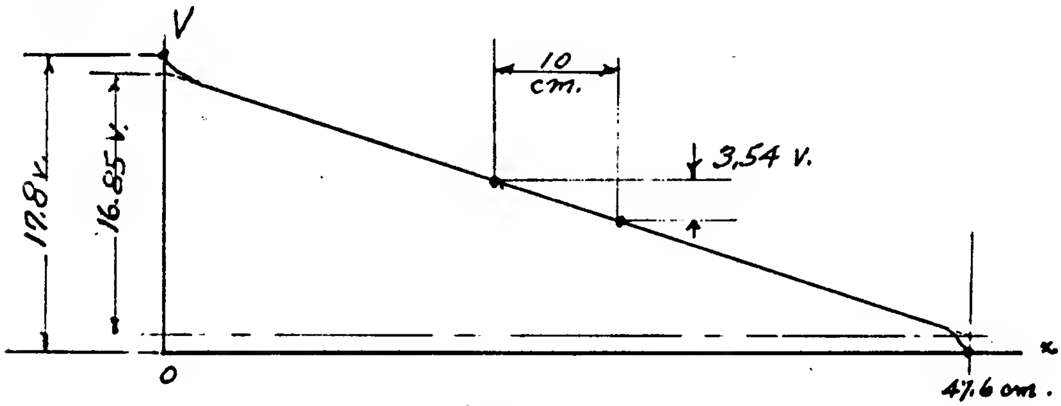


Fig. 14

At the current density of 0.016 amps/cm^2 there was only very slight polarization, about 0.5 volt at each electrode. The current density was 157 amps/m^2 with potential gradient 35.4 volts/meter. The corresponding conductivity is 4.43 mhos/m. In nine experiments at various currents, the average value for σ was, however, only 4.25 mhos/meter.

To guard against metal corrosion due to galvanic action of the currents at the electrode faces, a preparation was made of colloidal graphite and coated on the aluminum surfaces. This material consists of 225 cc ethyl ether mixed with 225 cc methanol, to which is added, with stirring, 50 cc of 5% collodion. This mixture was then slowly added, while agitating, to 125 gm "Aquadag". It was hoped that the resulting carbonaceous coating, which would be expected also to be water-insoluble, would be inert as far as electrochemical action was concerned. (Large electromagnetic submarines might use graphite electrodes).

9. STRUCTURAL DESIGN PROBLEMS

Decisions must be made regarding the simplest workable design for the center section containing magnet and batteries, the nose and tail sections, and the means of joining the three sections together. Also, how may the electrodes be joined to the hull in a water tight, electrically insulated manner?

9. STRUCTURAL DESIGN PROBLEMS

The center section had to be strong and rigid, as it supported the batteries and magnet coil. It also carried the mast, on which in turn was mounted the sail and instrument box.

A section of used 18" steel water well casing was located, from which was fabricated by burning and welding, the assembly shown in Fig. 15.

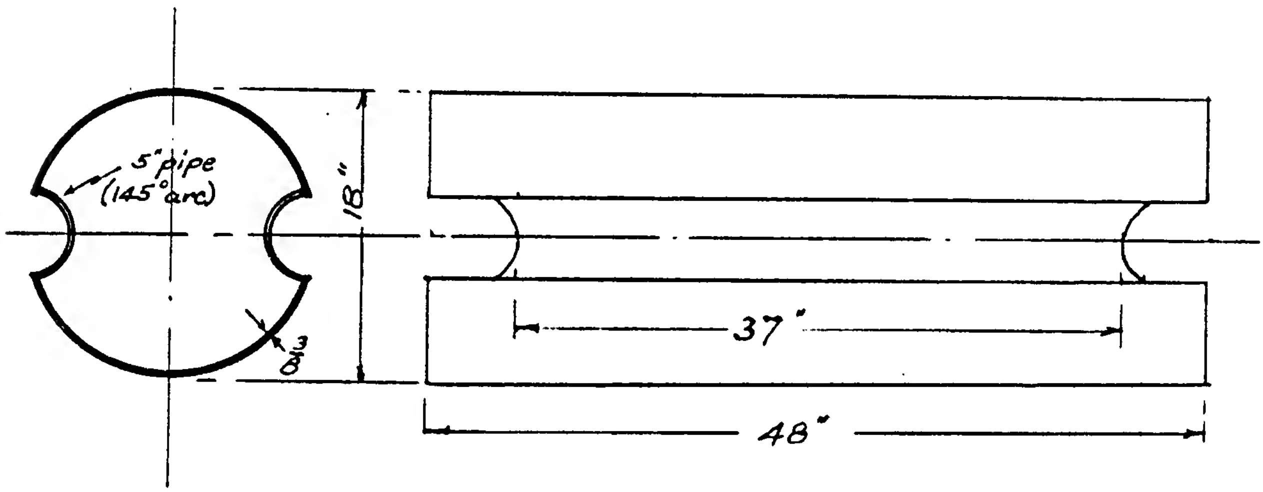


Fig. 15

It was necessary to finish the exterior cylindrical surface. University lathes could not handle this job and an outside shop* was found to do the machining. Ends were trued up in the same operation. Stiffening rings had also been added at either end to help preserve the cylindrical shape, as the cutting and welding produced distortion, and the pipe was not very true at the start. It was fortunate that the surface finally cleaned up with a minimum of 3/16 wall thickness finally being realized. Final O.D. was 17 11/16.

It was decided to make nose and tail cones of molded glass reinforced plastic. A problem was presented of joining these shells, which had about 3/16" wall thickness, to the steel center section. The joint had to be water tight and sufficiently strong to support the large buoyancy forces acting on the nose and tail sections.

* Westwick Iron Works, Santa Barbara

The joint problem was solved by use of a mounting ring on each end of the center section and a built-in steel ring in the nose and tail section. See the sketch in Fig. 16. The L - shaped mounting rings are assembled to the center section first. Then nose and tail cones are bolted in place, by inserting the allen screws from inside the hull center section. Tapped holes are used in the nose and tail section rings. Punch marks and scribed lines are used to identify mating parts and their proper orientation, to insure alignment of drilled and tapped holes. Sealant such as Permatex is used in metal to metal fits.

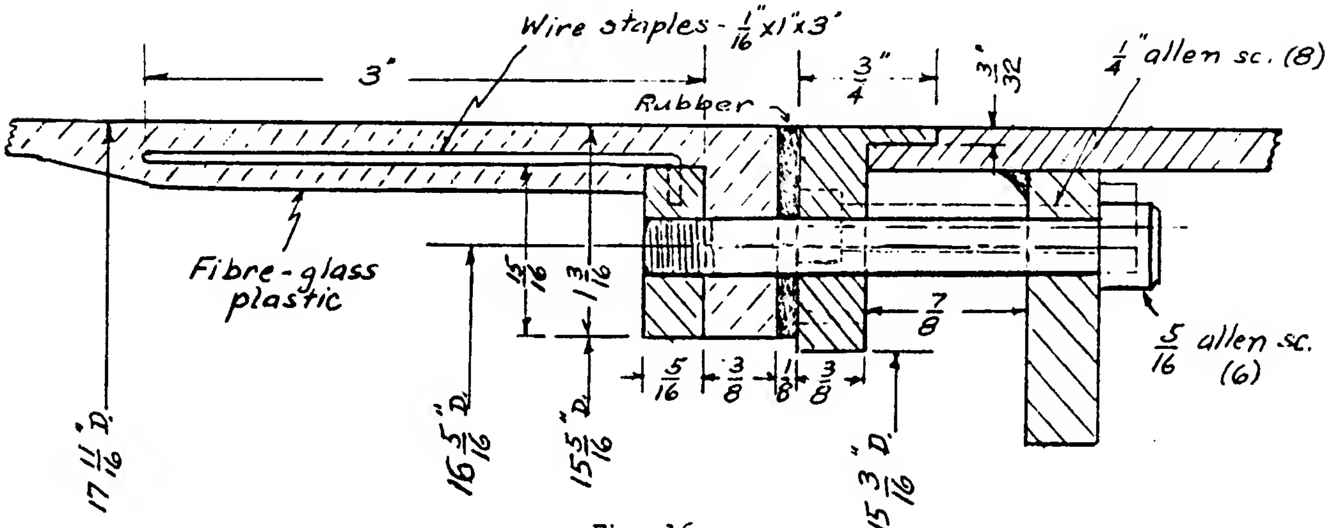


Fig. 16

With six 5/16" Allen screws to hold the nose and tail sections in place, equally spaced, 16 5/16" bolt circle, an amply strong attachment is provided.

The fabrication of the nose and tail sections (the tail section was truncated at a length of 36", with a 6 1/16" dia base at the small end) had to be carried out in such a way that the final exterior shape of the plastic sections would be smooth and true in shape.

How can this be accomplished? The method used is described below:

a) 4x4 wood pieces (actual finish about 3 9/16 x 3 9/16) were glued together to form approx. 18" square solid wood structures, 24" and 48" long. Fir wood was used. These were sent to a wood worker, Mr. Percy Beck,

for turning, since a suitable lathe was not available at the University. These pieces were accurately shaped to the desired exterior form of the nose and tail sections.

b) Molds were made of fiberglass reinforced plastic on the outside of these wood blocks.

c) These female molds were used to form the final nose and tail sections. The steel rings with the staple reinforcing were inserted in the molds and the plastic and fibre glass were formed around them.

d) Final sanding and buffing was done on the nose and tail sections, and ends were trued up. Holes were drilled and tapped.

Several problems arose in connection with fabrication of the nose and tail cones. First of all, fir wood proved to be an unfortunate choice. Redwood should have been used. The wood turning, with fir, was a laborious operation. Redwood could have effected a saving of time and money. A minor mishap resulted when it was discovered that a machine shop type drawing is not always the most suitable in a wood working shop. Dimensions should be in fractions, not decimals of an inch, etc. Some modification was made in the tail cone dimensions. (The offset dimensions previously given do not reflect this shop-change or take the modification into account).

Total cost of wood, wood turning, and fibre-glass fabrication was about $500, making the nose and tail sections the most expensive single components in the whole model. Still, however, the cost is low by present day project cost standards.

Construction of the tail surfaces, mast, sail and instrument box was fairly straight forward. The mast proper was a 3/4" steel pipe joined to the main hull by oval flange, screws and an interior nut on the end of the tube. A stream lined strut (3" chord and 1 1/8" thickness), with plastic guides at top and bottom, envelops the mast, and forms a support for the sail structure.

The sail is made of balsa, with plastic finish. (Foam material was also considered). Sail and stream lined strut could easily swivel, as a weather vane. In this way, the sail would always align with the water flow and never present a tilting moment. The water proof instrument box, with only the switch exposed, and hermetically sealed meters, was mounted on a flange at the top of the mast tube.

Tail sections are made of hardwood boards, and mounted with firm (rubber) frictional restrainers, so they stay in any alignment initially given them before a test.

The problem of attaching the electrodes to the hull consisted of two factors : the joint had to be water tight over the full length of about 46", and it had to be electrically insulating.

Aluminum angles were first joined securely, and with sealant, to the electrode shells. The whole assembly was then screwed in place over tape and sealant interlay with nylon screws. The problem would have been somewhat more difficult without the nylon screws.

Dwg. 852A176

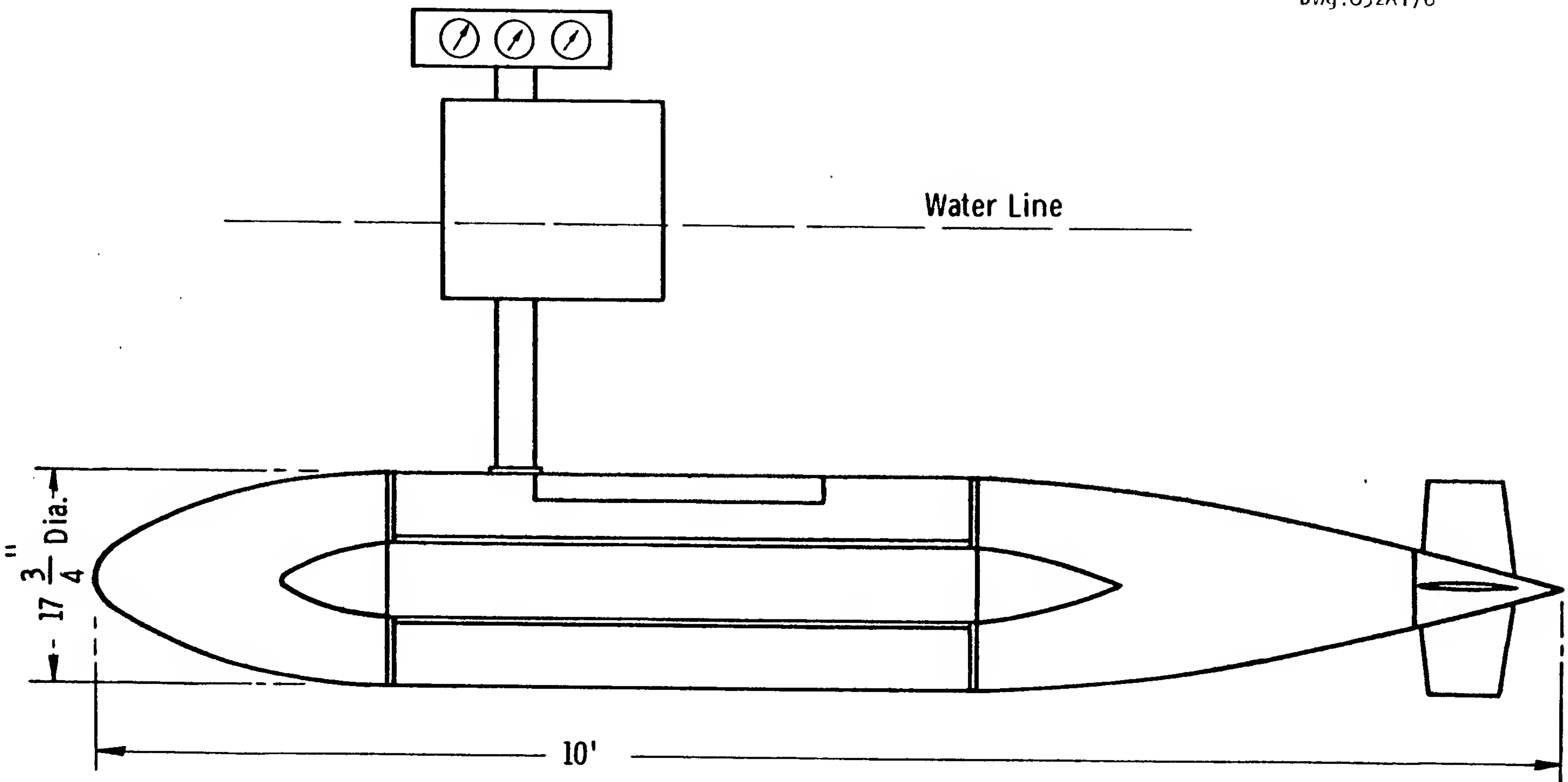


Fig. 17–Electromagnetic submarine model

10. ASSEMBLY PROBLEMS

Among the problems that arose, and which are discussed in this section, the most serious was that of the magnet coil tending to become too large to fit inside the electrode casings, since wires will not lay in a closely packed array as had been assumed in the original design.

Another problem was that of chafed insulation on the magnet winding giving a short to ground.

10. ASSEMBLY PROBLEMS

The construction of this model did not always work out in the most smooth and agreeable manner.

We have already alluded to the distortion that was observed in the center section weld assembly, due principally to cutting the 18" pipe and releasing the residual stresses. For a while, there was considerable concern about the possibility of giving the outside a finish cut in the lathe; we feared the model would turn out oval and badly distorted.

Other inconveniences arose because of inadequacies of the lathes in the University shop. The lathe could swing the diameters of the parts, but there was no room for the carriage to pass underneath the part.

The principal problem on assembly had to do with the magnet. As was mentioned previously, the magnet design calculations were made on the assumption of "tightly packed" wires. When it came to winding the heavy magnet wire, all manner of straining and pulling and careful application could not cause the wires to lay in anything remotely approaching a hexagonal (close packed) array. Calculations of the crushing force due to tension in the wire and turns also began to cause alarm, and braces were inserted as a precaution, during winding. The wires, toward the end, showed signs of bulging outwardly to a very considerable degree. We began to wonder how the electrode shells could ever be set in place.

One redeeming characteristic was that the bundle of wires was relatively "soft". It was found that by pushing radially inward on it, by means of improvised U-bolts and 2" x 4" wood levers, the wires could be caused to recede to approximately their desired location. However, the winding still had to be held in this "tight" condition. Sections that had been cut in forming the 6" dia. electrode shells were used as pads over the wires, and many ties of 3/32" stainless steel marine cable were applied, through drilled holes, to

secure the entire bundle firmly in place. As it finally turned out, the electrode height, out from the hull, became about 3/8" more than in the original design.

In the process of winding the magnet wire, with all the prying and pulling, it was finally discovered to everyone's horror that the coil was grounded . Since we used an ungrounded electrical system, one grounded point does not matter. A second ground in a new location could cause trouble. The ground appeared to be near the midpoint of the magnet winding (from potential difference checks).

In water proofing of joints, use was made of such products as marine bedding compound and Silastic cement.

11. RIGGING FOR TEST

By preliminary, on shore weighings, calculations and tests it was essential to be assured that when the model was placed in the ocean it would have (a) correct buoyancy within the range 0 to + 4 pounds, (b) approximately correct trim, that could be corrected at the same time as the final buoyancy adjustment in the ocean.

How to assure this?

11. RIGGING FOR TEST

A summary is given on the attached table of the design weight and balance calculations. On the basis of these it was anticipated that ballast would have to be added.

The model was finally weighed in its entirity, and battery weight was added. Calculations of volumetric displacement yielded a figure for the weight of the displaced sea water. Ballast (lead blocks) was added amidships and in the tail to partially compensate for the excess buoyancy, about 20 lb. margin being left.

We next constructed an immersion tank that was filled with fresh water. The assembled submarine was lowered into this tank. After two trials, weight and trim were adjusted for fresh water conditions.

It was obvious that when the model, with this amount of ballast, would be placed in sea water, it would be about 25 - 27 lbs too light. Consequently, we added about 22 lbs more lead amidships (just ahead of the c.g.). When the submarine was placed in the ocean, then, additional ballast could be added to either of two aft trim tanks. This final 3 - 4 lbs ballast was in the form of mercury. It was found that the trim and ballast adjustment in the ocean presented no problems.

A minor problem, mainly due to shortage of time to do an adequate job, arose in regard to locating and supporting the aft trim tank, which was far back in the tail section. With considerable contortioning and acrobatics, this aft tank, together with some required ballast weights, were finally installed, with the aid of marine bedding compound. The trim tanks were connected with the exterior by plastic tubes; rubber stoppers sealed off these tubes where they came through the plastic wall of the tail section, to the outside.

In regard to the weight and balance situation, the table on the

following page indicates that, with respect to the center point of the center section the center of buoyancy is located 3.3" aft, while the center of gravity, before adding ballast, is 0.47" aft. Also, the center of gravity is only 0.30" below the hull centerline. Center of buoyancy calculation disregarded any benefit of partial submersion of the sail. Though the estimated model weight of 762 lbs turned out to be somewhat lighter than the actual final weight without ballast, it was found to be necessary to add close to 100 lbs of ballast. This material, in the form of lead bars and BB shots, and finally mercury in the aft trim tank, was generally placed in the bottom of the hull, and toward the aft end. This tended to improve the stability by further lowering the center of gravity, while at the same time improving the trim adjustment. The lowering of the center of gravity by the ballast addition was approximately 1" .

Weight and Balance Estimates.*

Item	Weight	X	M_x	Y	M_y
Center section	176.0	0	0	0	0
Hatch cover	16.5	0	0	0	0
Batteries (5)	340.0	0	0	-1.9	-646.0
Binding posts and panel	4.0	16.0	64.0	6.0	24.0
Magnet winding	131.0	0	0	0	0
Electrodes (2)	13.1	0	0	0	0
½" angle	6.6	0	0	0	0
Battery connectors	3.3	0	0	0	0
Battery rack	6.7	0	0	-6.8	-45.2
Paint	1.0	0	0	0	0
Struts (2)	2.6	0	0	0	0
Nose cone	13.3	30.6	408.0	0	0
Rings (2)	8.0	0	0	0	0
Bolts (12)	0.6	0	0	0	0
Staples (60)	0.4	0	0	0	0
Tail section (frustum)	18.2	-38.4	-700.0	0	0
End plate	0.7	-59.3	-41.5	0	0
Glass plastic on end plate	0.5	-59.4	-37.9	0	0
Sail	3.0	13.0	38.8	31.0	93.0
Switch	1.5	14.0	21.0	38.8	58.2
Meters	1.0	14.0	14.0	38.8	38.8
Instrument panel	1.0	14.0	14.0	38.8	38.8
Pipe (mast)	3.0	14.0	40.8	23.8	71.4
Shroud (mast)	1.0	14.0	13.7	23.8	23.8
Electrical leads (5)	4.8	14.0	66.5	23.8	114.3
Mast bottom flange & nut	0.3	14.0	4.2	9.0	2.7
Tail, end cone(foam &glass)	0.5	-63.5	-33.2	0	0
Fins (4)	1.7	-63.5	-107.0	0	0
Rods and nuts	1.5	-62.5	-93.8	0	0
Bolt,nut,washer (tail joint)	0.5	-59.5	-29.7	0	0
	762.3	-0.47	-358.8	-0.30	-226.2

* Coordinates X and Y taken with origin at center point of center section. X positive in forward direction, Y positive upward. Units: inches and pounds.

Calculated C.G. of model: $\bar{X} = -0.47"$; $\bar{Y} = -0.30"$. A minor mistake which appears in the students'final report, in M_y and $\bar{Y}$, has here been corrected.

Buoyant Force and Center of Buoyancy.

Item	W_B	x	M_x	y	M_y
Bare hull values from students'report	829.23	51.7	42850	0	0
Tail modification	-8.29	89.5	-742	0	0
Correction for electrodes	60.4	48.0	2900	0	0
Correction for tail fins	3.6	112.0	403	0	0
	884.9	51.3	45411	0	0

Origin for coordinates x and y at front of nose. x positive in aft direction. We see that $\bar{x} = 51.3"$. In terms of coordinate X we have the C.B. at $\bar{X} = -3.3"$

12. TESTING EXPERIENCE

Thought must be given to the problem of putting the vehicle in the water, holding it while making ballast and trim adjustment, starting and stopping, model retrieval and removal from the ocean.

12. TESTING EXPERIENCE

This section will not attempt to go into detail on any but the first two tests of this model, which by now had been named the EMS - 1*.

The first test, on July 20, 1966, made off Goleta pier, Santa Barbara County, California, involved carrying the model to the pier by means of a small flat bed trailer, hoisting it into the water by means of a sling and spreader rig, and then attempting to unhook the model and balance it, by adding mercury to the trim tanks. (If this were accomplished, the model was to be set in operation). However, even a slight swell of about 10" amplitude made it impossible to manage the 900 lb model in the water during the attempted balancing operation. Wind and current added to the difficulties. Naturally, there were great fears of the model smashing against the dock or the accompanying rowboat. The model was secured by line to the rowboat, the oarsmen meanwhile trying to keep the whole affair in open water, against the action of the wind and waves.

In this rather trying situation, the rubber stopper from the aft trim tank became dislodged. Water ran in, and, apparently by some mishap also with the plastic connecting tube, began flooding the tail section. At this point, the group proceeded with all haste toward the shore, the tail of the submarine drooping deeper and deeper by the second. Fortunately, no ballast shift occurred. Batteries are securely held and can not shift.

The shore, initially 50 yards away, was reached, and after some difficulties the submarine was finally beached through the breakers and dragged up on the shore.

It was discovered that no major damage had occurred. It was only necessary to clear the water from the hull interior, make adjustments of rudders and repair the minor damage to the trim tanks. Rubber stoppers were replaced by sealed screws.

*Electromagnetic Submarine No.1 .

On July 21, 1966, at noon, a second test was made. This was at the yacht basin in Santa Barbara, a very calm body of salt water with sloping concrete access ramps. Launching was easily accomplished by means of a "dolly". Trim was adjusted. In about 5 ft. of water, with water line about 3" above the bottom of the sail, and the hull level, the starting switch was closed.

The model gradually accelerated. The calculated acceleration pattern is indicated in the following tabulation:

V m/sec	% of design speed	t (sec)
0.05	12.8	16.2
0.10	25.6	34.2
0.15	38.4	56.8
0.20	51.2	86.5
0.25	64.0	136.5
0.30	76.8	240
0.35	89.6	600
0.40	100.0	

It appeared that, if anything, the model accelerated more rapidly than the above theoretical tabulation would indicate.

Runs of 50 -60 meters parallel to the shore were performed. Observers on shore were of the opinion that speeds of nearly 0.5 meter/sec were reached. With slow and easy swimming one would keep ahead of the model. Circular runs were also made on July 21 by displacing the rudders. Total cruise time was about 12 minutes, with batteries not yet exhausted.

The mercury starting switch operated quite satisfactorily; switch freeze-up is impossible. Testing is most easily carried out in water of 5 ft depth, permitting the test crew to manually start,stop, guide or retrieve the model; however this shallow water places the model at a disadvantage in performance. 3/8" stainless eye-bolts on the top af the center section, fore and aft, also facillitate handling.

13. SUMMARY OF THE UNANTICIPATED PROBLEMS

a. Warpage of the hull center section weld assembly after relieving the residual stresses by cutting the 18" pipe.

b. Difficulties with fabrication of wood molds for fiber glass parts from fir wood.

c. Available wire lengths in coils compelling compromises in magnet winding design.

d. Bulging of the magnet wire while winding the magnet coil, and necessity for compressing and clamping the winding.

e. Difficulty in joining electrode shells to the center body, until nylon screws were located.

f. Susceptibility of filling plugs to dislodgement, and inadequacy of design of the aft trim tank installation.

g. Even very mild ocean waves were found to greatly complicate the handling and balancing of the model; calm water is essential. 10" waves with an 18" diameter model are similar to 20 foot waves with a 36 foot diameter submarine.

h. Handling of the model on shore was difficult and sometimes dangerous. Adequate hoisting facilities should be provided wherever possible rather than depending on strong backs; weight without batteries is 560 lbs.

Some thought had previously been given, in the latter stages of design, to the various possible failures that could occur. Among these were (a) model misses anticipated match of buoyancy and weight by a wide margin, (b) due to a leak model may sink in deep water, (c) gas bubbles reduce effective conductivity, (d) due to electric break-down and arcing a fire occurs inside the hull, (e) elec-

trodes may be smashed by a collision. Problem (a) was minimized by careful calculations, weighings where possible and finally immersion of the model in a specially constructed wooden tank in the assembly area. (b) was minimized by confining all initial tests to water of moderate depth of less than 20 ft, so that a swimmer could go down and secure a line to the eyebolts if necessary. These eyebolts were very accessible so that it would be easy to quickly attach a line, during a test , if the model showed a tendency to sink. (c) was investigated in the conductivity test mentioned in Section 8. In regard to (d) special attention was given to insulation of the conductors from one another and from ground, and all leads were anchored securely in place. To prevent damage to the model, as in (e), that could cascade to other problems, great care should be taken in handling, tests must be in calm water, and the model must be under complete control at all times. On July 20, 1966 we came very close having serious difficulties by insufficient attention to these matters.

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United States Patent Office

2,997,013
Patented Aug. 22, 1961

2,997,013

PROPULSION SYSTEM

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Filed July 18, 1958, Ser. No. 749,547
4 Claims. Cl. (115—11)

The present invention relates to a propulsion system for vessels traveling in an ionic media and more particularly relates to drive systems wherein the outer surface of the vessel constitutes an electrolytic cell employing the ambient ionic media as an operating electrolyte. Still more particularly the present invention relates to a vessel propulsion drive requiring no moving parts and wherein the thrust is accomplished electromagnetically to promote laminar fluid flow at the interphase between vessel and media.

The instant drive or propulsion system is applicable to all vessels, such as ships, submarines, torpedoes, and the like traveling in salt water. Insofar as can be experimentally shown the device also has utility as a space drive system for imparting thrust to a vessel travelling in an ionic atmosphere, for example, space.

It has long been known that when an electrical current is passed through a magnetic field that a thrust is accomplished which obeys the "left hand rule" and which is of a magnitude directly proportional to the magnetic field strength and the current density. Such electrical principles are applied in electromagnetic pumps for the handling, for example, of liquid material which is an electrolyte. Such a device is illustrated in United States Letters Patent 2,786,416, issued to Alan Stephen Fenemore on March 26, 1957.

Similarly, particle acceleration in vacuum tubes has demonstrated the concept of thrust obtained by intersecting lines of magnetic flux with a suitable current flow in an ionic atmosphere. Reference is made to United States Letters Patent 2,497,891, to Donald W. Kerst, issued on February 21, 1950.

However, until the instant invention there was no appreciation of the application of the known principles to the problem of propelling a vessel in an electrolyte and space.

It has now been found that the structural members of the vessel itself can be utilized to generate a thrust of sufficient magnitude to be useful. It has also been found that the flow obtained at the interphase between hull and fluid media is substantially laminar so as to impart an added credit to the concept of vessel propulsion by material reduction in friction.

Thus, the hull itself generates the force to propel the vessel and the hull form imparts direct surface thrust in contrast, for example, to prior art propeller propulsion and its accompanying turbulent flow.

Accordingly one of the objects of the present invention is to provide an electromagnetic drive for vessels moving in an ionic media.

Another object is to provide a propulsion means having its source substantially at the interphase between vessel hull and media.

Still another object is to provide a propulsion means integrated into the hull structure of the vessel to be propelled.

Still another object is to provide a hull surface capable of serving as a cell in an ionic media so as to provide desired electromotive force.

Other objects include the provision of a highly efficient propulsion means eliminating the necessity for intricate mechanical movements extending into the liquid media to require intricate and expensive seal means. These objects include obvious design simplification which can result

from the adoption of the presently described propulsion means.

In the drawings:

FIGURE 1 is a schematic perspective view of a tube across which is gapped a magnetic flux field and showing an E.M.F. crossing the gap using, for example, sodium chloride in water as the ionic conducting media, and indicating the direction of force generated by the tube.

FIGURE 2 is a perspective schematic view of a tube encasing, for example, the hull or shell of a projectile, vessel, or the like where the E.M.F. is generated by the cell established by the silver hull and the magnesium sleeve and where the magnetic flux lines are available from permanent magnets used as spacers.

FIGURE 3 is a schematic view of a device which also utilizes a cell created by structural portions of the hull separated by suitable insulating strips and having a permanent magnet internally oriented so as to establish magnetic flux lines intersectable by the E.M.F. established by the cell in the electrolyte to provide a thrust force in the direction indicated.

FIGURE 4 illustrates a hull structure in schematic cross section indicating a segmentalized external system of alternate North and South magnetic poles with alternating positive and negative plates supplied with an E.M.F. from a suitable generator and being conducted by the electrolyte or ionic media in which the hull is immersed.

FIGURE 5 illustrates in schematic perspective a system in accord with the present invention whereby the hull establishes an electrolytic cell and the magnetic flux density is obtained by the use of a generator served electro magnet.

General description

In electromagnetic phenomena it has long been known that if a current is passed across a magnetic field a force is set up which generally is dependent upon the flux D, the distance between conductors, and the amperage or current. The general formula may be expressed as:

$$\text{Thrust in kilograms} = (10.2 \times 10^{-8}\ [\text{flux density (gauss)} \times d(\text{centimeters}) \times I(\text{amperes})]$$

Conversion to pounds of thrust is accomplished by multiplying the thrust in kilograms by the rough factor of 2.2.

Experimental work based on this data has generally validated this above expression and supplementally has shown that the thrust is a reaction to the movement of the electrolyte through which the current passes. Viewed in a vacuum the thrust may be expressed in terms of ionic drive employing beta particle emission with the bonus obtained by appreciation of mass. Further, the flow pattern appears "laminar" in nature in contrast to a type of thrust imparted by a driven propeller, the latter being characterized as "turbulent." Peculiarly the laminar flow is substantially independent of hull design, that is, the hull design becomes considerably less critical assuming that the entire hull is used as a drive fixture.

In general a magnetic field is established using components of the vessel as alternate north and south poles. As between these structurally established poles a magnetic flux is established through an ionic media, for example, an ionized atmosphere such as space or an electrolyte such as salt water. An electric current, also emanating from the structural members of the vessel passes through the ionic media cutting the magnetic lines of force. The result is a movement of the electrolyte in obedience to the "right hand rule." The movement is equivalent to the force exerted in accord with the foregoing general formulation and a reaction force thus propels the vessel.

When the above expression is applied in space it can be said that hull members provide the magnetic field and that hull members also serve the function of anode and

and such modifications are intended to be included herein limited only by the scope of the hereinafter appended claims.

I claim:

1. In a laminar flow propulsion system for vessels in an ionic media, the combination comprising: a hull having external alternate divided skin surfaces where the alternation is between electrically conductive surfaces and magnetic sources for field flux generation.

2. In a propulsion system in an ionic media the combination including: a magnetic field spanning a part of said ionic media; an electromotive force passing through said ionic media and cutting said magnetic field at substantially right angles; and a hull structure, the external surface of which serves to generate said field and from which emanates said electromotive force.

3. In a propulsion system for vessels in an ionic media, the combination comprising: a hull structure; a pair of magnetic poles structurally integrated in said hull; a pair of electrodes structurally integrated in said hull and arranged to pass an electromotive force across a magnetic field established between said poles external of said hull; and means generating an electromotive force supplying said electrodes.

4. In a propulsion system for vessels in an ionic media, the combination comprising: a hull segment serving as an

electrode; a substantially concentric annulus in spaced apart relation from said hull and also serving as an electrode; a plurality of magnetic spacers insulated from said electrodes and in spaced apart position, the north pole of one magnet spacer facing the south pole of the next adjacent spacer member; and a source of electromotive force applied to said electrodes whereby in cutting magnetic lines of force between said magnet spacers, a flow is established in said ionic media, the reactance to said flow propelling said hull.

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PROPULSION SYSTEM

Filed July 18, 1958

FIG. 1

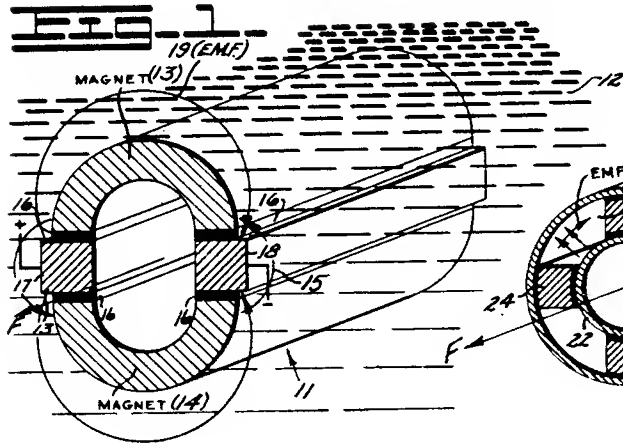


FIG. 2

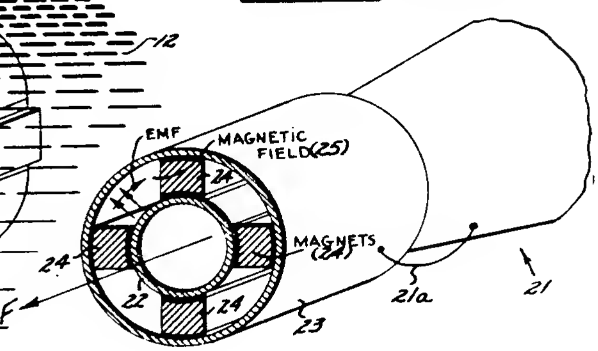


FIG. 3

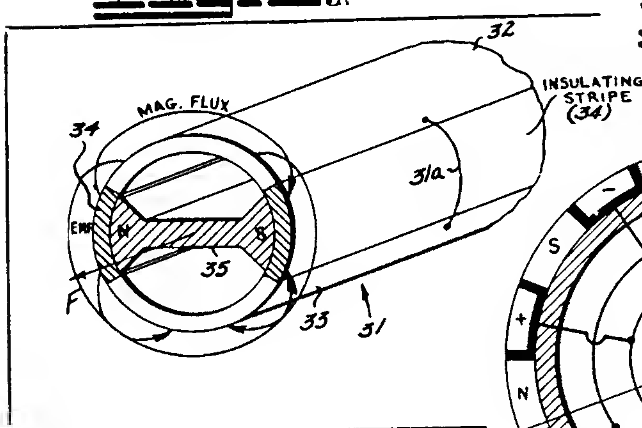


FIG. 4

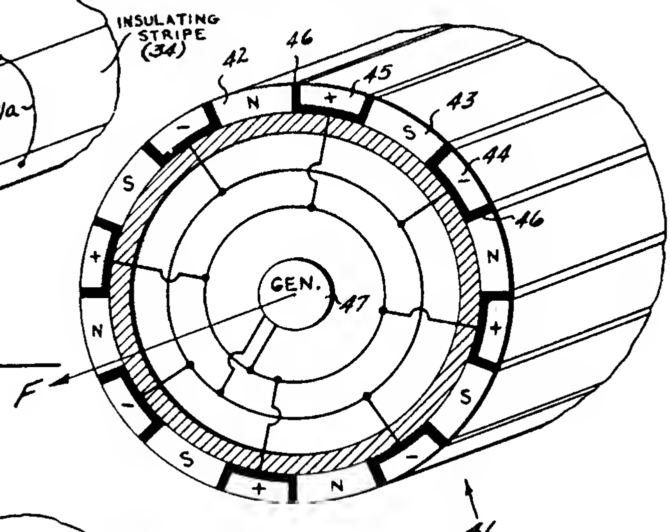
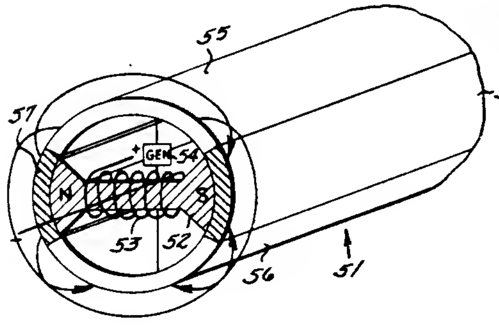


FIG. 5



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INSTRUCTOR'S NOTE

There are two ways in which this Case Study might be used in the engineering educational program.

One use would be as a basis for development of engineering design problems and studies. Thus, the design class might be presented with the questions, inquiries, problems and difficulties that arose in connection with the design and construction of this model. They would be required to face up to these problems and questions, and reach certain design decisions, which could be compared with those reached in the Santa Barbara project. It would also be possible to pluck out isolated topics as design problems, such as electromagnet optimization, if the instructor did not wish to follow through on the entire submarine model project.

The second use that could be made would be as a project guide or reference work in the event that the instructor and his class chose to pursue their own electromagnetic submarine project. The writer would like to encourage this course. Undoubtedly, improvements could be made, based on the Santa Barbara model experience. Other, and perhaps more rewarding design approaches could be investigated. In this way, the class would have its own real engineering experience, and would have the satisfaction of pushing forward the engineering technology of this type of devices.

S. Way